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PULSE POWER EFFECTS IN DISCRETE RESISTORS

Clarkson College of Technology
Potsdam, NY 13676

November 1976

Final Report

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Prepared for
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Washington, DC 20305

AIR FORCE WEAPONS LABORATORY
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This technical report has been reviewed and is approved for publication.

BRUCE S. HUEHN
Sgt, USAF
Project Officer

FOR THE COMMANDER

DONALD C. WUNSCH
Acting Chief, Applied Research Branch

JOHN S. DeWITT
Lt Colonel, USAF
Chief, Technology Division

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The object of this report is to study pulse power failure of carbon composition, wire-wound, and carbon film resistors. For each type of resistor, the materials, construction techniques, manufacturer's specifications, calculations on transient temperature rise, and experimental data are given.

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SECTION I

INTRODUCTION

This report is a study of Electromagnetic Pulse (EMP) effects on discrete resistors. The primary emphasis has been on calculating the transient temperature rise during a single pulse ranging from 10 nsec to 100 μsec in duration, although voltage breakdown can be the dominant failure mechanism for very short pulses.

The temperature rise during pulse operation of metal film and film-type carbon composition resistors has been reported earlier.[1] This study is a continuation dealing with carbon composition, wire-wound, and carbon film resistors. Resistors from six different companies were investigated. The fabrication method, construction details, materials, and electrical performance specifications were compiled. Estimates of peak temperature rise were made, and, in some cases, experimental data was taken on pulse power failure.

Section II deals with carbon composition resistors. Wire-wound resistors are treated in Section III, especially with regard to properties of the wire made by several manufacturers and used in nearly all of the domestically produced wire-wounds. Section IV discusses carbon film resistors.

SECTION II

CARBON COMPOSITION RESISTORS

Carbon composition resistors are made by several manufacturers in this country. Samples were received from two companies; Allen-Bradley, Milwaukee, Wisconsin, and TRW Electronic Components, Philadelphia, Pennsylvania. Resistors from both companies are covered by military specification MIL-R-39008A. A typical designation is shown below in Table 1.

Table 1. MIL-R-39008A designation.

RCR05G203JS

TYPE

Fixed Composition Resistors, Insulated, Established Reliability

STYLE

05	1/8 watt at 70°C
07	1/4 watt at 70°C
20	1/2 watt at 70°C
32	1 watt at 70°C

CHARACTERISTIC

Symbol	Max. ambient operating temp. (100% rated wattage)	Resistance–temperature characteristic		
		Nominal resistance (ohms)	Max. allowable change in resistance from resistance at ambient temp. of 25°C	
			At −55°C	At +105°C
G	70°C	1,000 and under	±6.5%	±5%
		1,100 to 10,000	±10%	±6%
		11,000 to 0.1 M	±13%	±7.5%
		0.11 M to 1.0 M	±15%	±10%

FAILURE RATE LEVEL

At 50% rated wattage expressed in %/1000 hrs.

M = 1.0%
P = 0.1%
R = 0.01%
S = 0.001%

RESISTANCE	TOLERANCE
J	± 5%
K	±10%

RESISTANCE

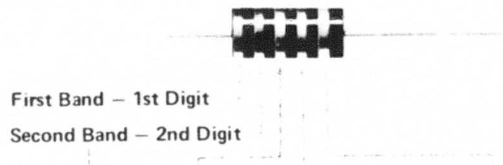
Expressed in ohms and identified by a three-digit number. First two digits represent significant figures. Last digit specifies the number of zeros to follow. For values below 10 ohms, the letter "R" is substituted for one of the significant digits to represent the decimal point, and the following digits represent significant figures.

Example: 2.7 Ohm = 2R7

2

The resistors are color-coded with four or five bands. The first three bands (starting with the band closest to one lead) are the standard color-code for the resistor value. The fourth band indicates the tolerance while the fifth band specifies the failure rate. This is summarized in Table 2.

Table 2. MIL-R-39008A color code.



Color	Digit	Multiplier	Tolerance	Reliability Level ■ (Percent Per 1000 Hours)
Black	0	1	–	–
Brown	1	10	–	M = 1.0%
Red	2	100	–	P = 0.1%
Orange	3	1000	–	R = 0.01%
Yellow	4	10,000	–	S = 0.001%
Green	5	100,000	–	–
Blue	6	1,000,000	–	–
Violet	7	10,000,000	–	–
Gray	8	–	–	–
White	9	–	–	–
Gold	–	0.1	±5%	–
Silver	–	–	±10%	–
No color	–	–	±20%	–

■ When Applicable

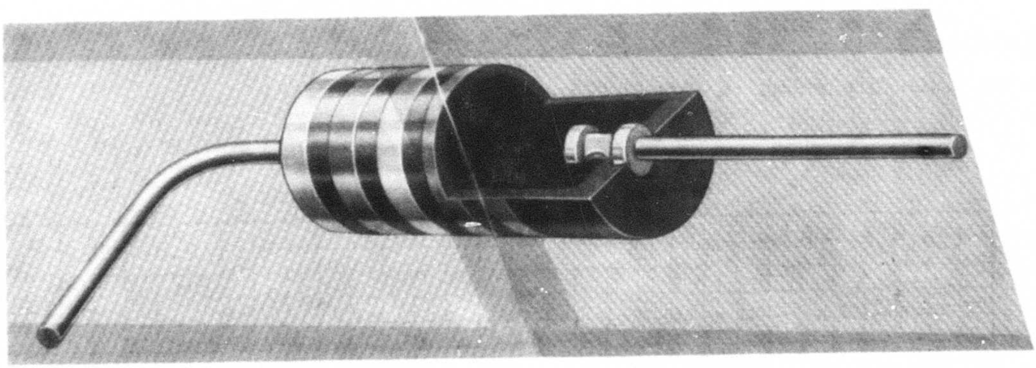


Figure 2-1. Carbon composition resistor made by Allen-Bradley.

A view of an Allen-Bradley resistor is given in Figure 2-1. The resistors are made by a hot-molding process in which the leads, resistance material, and jacket are fused simultaneously. The insulating jacket is a mineral-filled phenolic. The inner core is the same material with carbon added to provide a conductive path between leads. The carbon content is adjusted to achieve the desired resistance value.

The leads are oxygen-free copper, coated with solder. The end which is imbedded in the resistor body is swaged for better mechanical strength. On two-watt resistors, the shape is an inverted taper. On all other resistors, the lead end is normally a double nailhead as shown in the Figure. For low values of resistance, below 100 ohms, the end is knurled to lower the contact resistance between the lead and the carbon slug.

Resistor dimensions and weights are listed in Table 3. External dimensions and weights are those given by the manufacturer. Internal dimensions were measured on cross-sectioned resistors and vary considerably from resistor to resistor. Dimension G, for example, was 3.4 mm for a 12 ohm, 1/4 watt resistor and increased to 4.3 mm for a 30,000 ohm, 1/4 watt resistor. According to the manufacturer, however, this spacing is not intentionally altered. Dimension G is recorded in the table for 820 ohm resistors. Performance characteristics are listed in Table 4.

The temperature coefficient of resistance for carbon composition resistors is large and nonlinear. Typical temporary resistance changes due to temperature are shown in Figure 2-2.

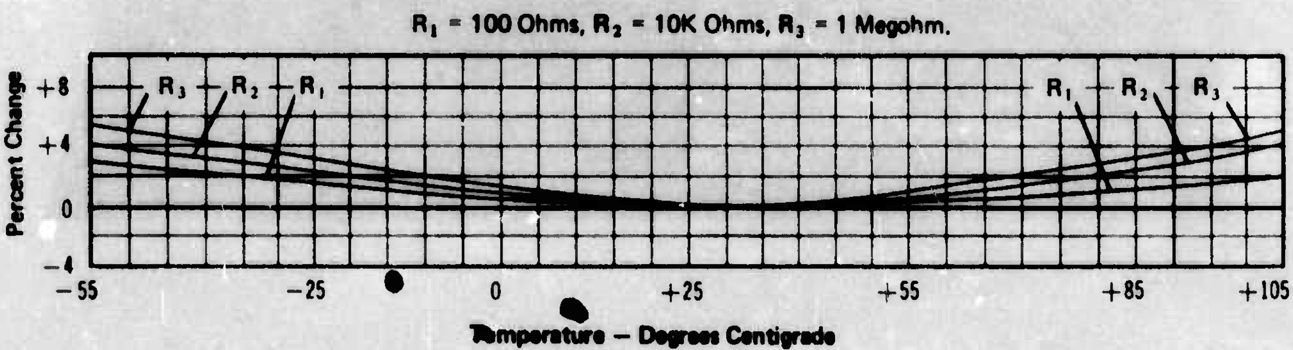


Figure 2-2. Change in resistance due to temperature

Table 3. Resistor dimensions and weights for Allen-Bradley carbon composition resistors. Lengths are in millimeters.

A-B Type	Military Designation	Rating in Watts	A	B	C	D	E	F	G	Total Weight grams	Lead Weight mg/mm
BB	RCR05	1/8	3.68	1.59	25.4	0.38	3.03	1.01	2.29	0.077	1.2
CB	RCR07	1/4	6.35	2.29	38.1	0.64	5.08	1.40	4.07	0.28	2.9
EB	RCR20	1/2	9.52	3.56	38.1	0.84	7.62	2.41	4.95	0.61	5.0
GB	RCR32	1	14.3	5.72	38.1	1.05	11.4	3.94	8.38	1.45	8.0
HB	RCR42	2	17.5	8.08	38.1	1.14	12.7	5.72	7.11	2.80	9.4

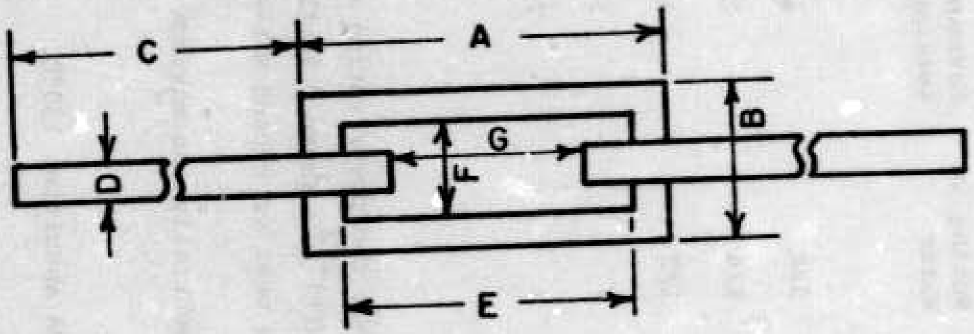


Table 4. Electrical performance characteristics of Allen-Bradley resistors.

A-B Type	Rating in Watts	Maximum Continuous Working Voltage[1]	Dielectric Withstanding Voltage[2]	Maximum Temperature at Rated Power	Power Derated Linearly to[3]
BB	1/8	150	300	70°C	130°C
CB	1/4	250	500	70°C	150°C
EB	1/2	350	700	70°C	150°C
GB	1	500	1000	70°C	150°C
HB	2	750	1500	70°C	150°C

[1]Provided that the power rating is not exceeded, in which case the maximum voltage is $(PR)^{1/2}$, where P is the power rating and R the resistance value. These raings meet or exceed MIL-R-39008A.

[2]This is essentially the maximum allowable rms voltage between the leads and the jacket.

[3]MIL-R-39008A specifies 130°C.

Resistance changes due to an increase in moisture content are always positive but can be prevented by operating the resistor under load or eliminated by baking at 100°C. Voltage coefficients of resistance are negative and range from -70 to -550 ppm/volt. Resistance changes during load life are permanent and negative, less than 2% during thousands of hours at 50% rated power.

Sometimes the EMP pulse is specified by its frequency spectrum rather than its time-domain waveform. In this case, the frequency response of the resistor is important. Carbon composition resistors tend to be capacitive at high frequencies although this depends greatly on length of leads, which contribute an inductive effect. High frequency response of Allen-Bradley resistors is shown in Figure 2-3.

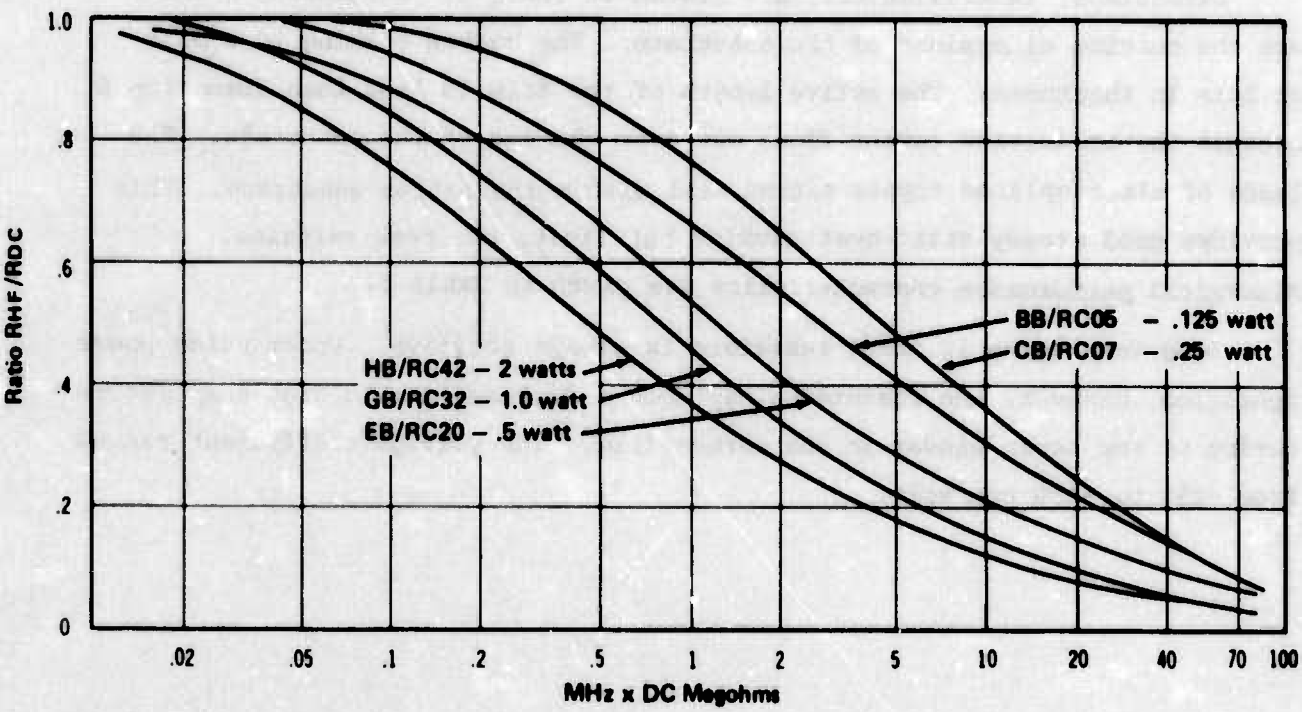


Figure 2-3. Typical high frequency characteristics of Allen-Bradley resistors.

The film-type carbon composition resistors made by TRW are fabricated by an entirely different process, but the fact that the conducting material is formed from carbon particles in a suitable binder makes them more similar to a

pellet-type composition resistor than to deposited carbon resistors normally referred to as carbon film resistors. Fabrication begins with the drawing of a hollow glass tube with carefully controlled inside and outside diameters. A layer of carbon in a lacquer binder is then applied. The thickness of the carbon coating (up to two mils) and the composition are carefully controlled and monitored to achieve the sheet resistance required for the final resistance. No spiralling or other trimming is done to adjust the resistance value. The film is cured at 535°C. The glass tubes are initially cut into two-foot lengths and tested, then cut into individual substrates. Swaged leads are inserted with a small amount of conducting cement to establish contact to the film. The jackets are compression-molded epoxy (1/4 watt sizes) or phenolic (1/2 and 1 watt sizes).

Dimensions, in millimeters, are listed in Table 5. Dimensions E and F are the outside dimensions of the substrate. The carbon coating is 2 mils or less in thickness. The active length of the film is less than dimension E because the conductive cement flows out over the end of the substrate. The leads of electroplated copper extend well within the hollow substrate. This provides good steady-state heat sinking but limits the peak voltages. Electrical performance characteristics are given in Table 6.

Long term aging in these resistors is always positive. Under pulse power operation, however, the resistance may show a decrease due to high temperature curing of the resin binder in the carbon film. The voltage coefficient ranges from -150 to -350 ppm/volt.

Table 5. Dimensions, in millimeters of TRW film-type carbon composition resistors.

TRW Type	Military Designation	Rating in Watts	A	B	C	D	E*	F
GBT-1/4	RCR07	1/4	6.4	2.29	38	.63	4.12	1.03
GBT-1/2	RCR20	1/2	9.9	3.56	38	.79	6.68	1.40
GBT-1	RCR32	1	14.3	5.71	38	1.01	10.3	1.75

*This is the length of the glass tube. The carbon film is reduced about 20% from this value by silver cement which contacts the leads.

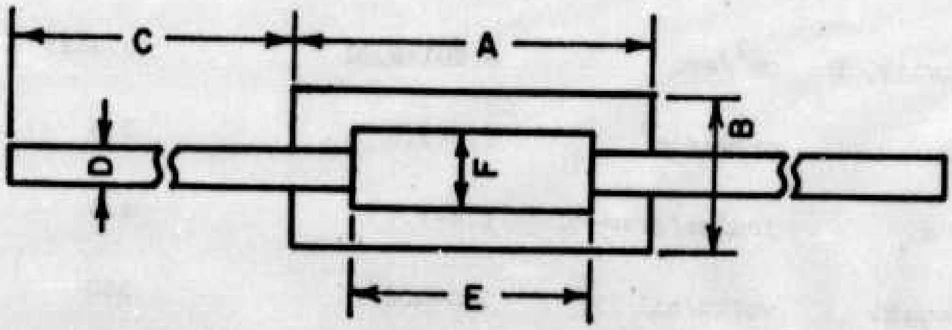


Table 6. Characteristics and performance of TRW Resistors

TRW TYPE	GBT-¼	GBT-½	GBT-1
MIL-R-11 Style	RC07	RC20	RC32
MIL-R-39008 Style	RCR07	RCR20	RCR32
MIL-R-39008 Failure Rate Level	S	S	S
Resistance, Standard	2.7 ohms thru 22 Megohms	2.7 ohms thru 22 Megohms	2.7 ohms thru 22 Megohms
Resistance, Special (Non Mil)		24 Megohms thru 100 Gigaohms	—
Tolerances, Standard	±5%, ±10%, ±20%	±5%, ±10%, ±20%	±5%, ±10%, ±20%
Power Rating	¼-watt @ 70°C	½-watt @ 70°C	1-watt @ 70°C
Maximum Continuous Working Voltage	250 Volts	350 Volts	500 Volts
Minimum Insulation Resistance—Dry	10,000 Megohms	10,000 Megohms	10,000 Megohms
Wet	100 Megohms	100 Megohms	100 Megohms
Minimum Dielectric Withstanding Voltage Atmospheric	500 Volts, R.M.S.	700 Volts, R.M.S.	1000 Volts, R.M.S.
Reduced	325 Volts, R.M.S.	450 Volts, R.M.S.	625 Volts, R.M.S.
Shunt Capacitance (Avg.)	0.15 pF	0.175 pF	0.25 pF
Load Life-Typical ΔR Less Than*	±4%	±8%	±6%

Resistance-Temperature Characteristic	Typical ΔR Less Than* From 25°C Reference					
Nominal Resistance (Ohms)	GBT-¼		GBT-½		GBT-1	
	@ −55°C	@ +105°C	@ −55°C	@ +105°C	@ −55°C	@ +105°C
1K and Under	±2%	±2%	±4.5%	±2.5%	±5%	±4%
1.1K to 10K	+8%	±3%	+7%	−2.5%	+8%	−4%
11K to 100K	+9%	−4%	+9%	−3.5%	+9%	−4%
110K to 1Meg	+10%	−5%	+10%	−3.5%	+11%	−4%
1.1Meg to 10Meg	+11%	−5%	+11%	−3.5%	+11%	−4%
11Meg to 22Meg	+11%	−5%	+11%	−3.5%	+11%	−4%

*"Typical ΔR Less than" is defined as the maximum ΔR to be expected in 95% of the population of Δ distribution.

High frequency characteristics are similar to, but slightly better than those of typical slug-type composition resistors.

In order to calculate the temperature excursion of a resistor during an EMP pulse, the thermal properties of the materials must be known. Unfortunately, exact values are usually difficult to obtain. Properties of mineral-filled phenolics, obtained from the literature,[2,3,4] are listed in Table 7.

Table 7. Properties of mineral-filled phenolics.

Property	Units	Range	Selected Value
thermal conductivity, k	watts/cm-°C	0.003-0.01	0.005
thermal diffusivity, D	cm^2/sec	0.001-0.01	0.0015
density, ρ	grams/cm^3	1.5-2.3	2.3
specific heat, c	joules/gram-°C	1.4-1.7	1.5
dielectric strength	volts/mil	200-400	350
maximum useable temperature	°C	160-260	225

The selected values are thought to be reasonable estimates for the Allen-Bradley resistors. Assuming that the carbon content of the resistor core is small, the values should apply to both the core and the insulating jacket.

In assessing the pulse-handling capability of slug-type composition resistors, the geometry of the resistor and its heat capacity dominate the issue entirely. It can be shown that for a single pulse from 10 nsec to 100 μsec long the temperature rise is determined by the pulse energy and the heat capacity of the core and is independent of the jacket, leads, or any external heat sink.

Consider a long circular cylinder imbedded in a perfect heat sink, initially at ambient temperature T_o. If a step function of power density P_o is uniformly applied throughout the cylinder with the heat sink maintained at ambient temperature, the temperature rise $T-T_o$ is given by[5]

$$T - T_o = \frac{P_o}{k}\left[\frac{(a^2 - r^2)}{4} - \frac{2}{a}\sum_{n=1}^{\infty} e^{-D\alpha_n^2 t}\,\frac{J_o(r\alpha_n)}{\alpha_n^3 J_1(a\alpha_n)}\right] \qquad (2\text{-}1)$$

where k is the thermal conductivity, a is the radius of the cylinder, r is the distance from the axis of the cylinder, D is the thermal diffusivity, and the α_n is determined from the roots of the zeroth order Bessel function $J_o(a\alpha) = 0$.

The peak temperature rise occurs at r=0 and is plotted in normalized form in Figure 2-4. The straight line asymptote is the limiting case of adiabatic temperature rise given by

$$T - T_o = \frac{D}{k} P_o t. \qquad (2\text{-}2)$$

When Dt/a^2 is less than 0.1, there is less than 5% difference in the exact and asymptotic solutions. For short pulses, then, the heating is adiabatic and the boundaries of the cylinder have no effect on the peak temperature rise. In terms of the diameter of the cylinder the above equation becomes, approximately,

$$L \leq \frac{1}{6} d \qquad (2\text{-}3)$$

where d is the diameter and L is the diffusion length given by

$$L = (Dt)^{1/2}. \qquad (2\text{-}4)$$

For the 1/8 watt Allen-Bradley resistor, using the dimensions from Table 3 and the thermal properties from Table 7, Equation (2-3) is satisfied for $t \leq 200$ msec. Hence the adiabatic approximation can be used for all the Allen-Bradley carbon composition resistors for any EMP pulse.

Temperature rise in film-type resistors has been treated in reference 1. Results which are applicable to the TRW resistors are repeated here for convenience. Thermal properties of the glass substrate, carbon film, and phenolic jacket are listed in Table 8. There is some question concerning the thermal properties of the carbon film. The conductivity and diffusivity

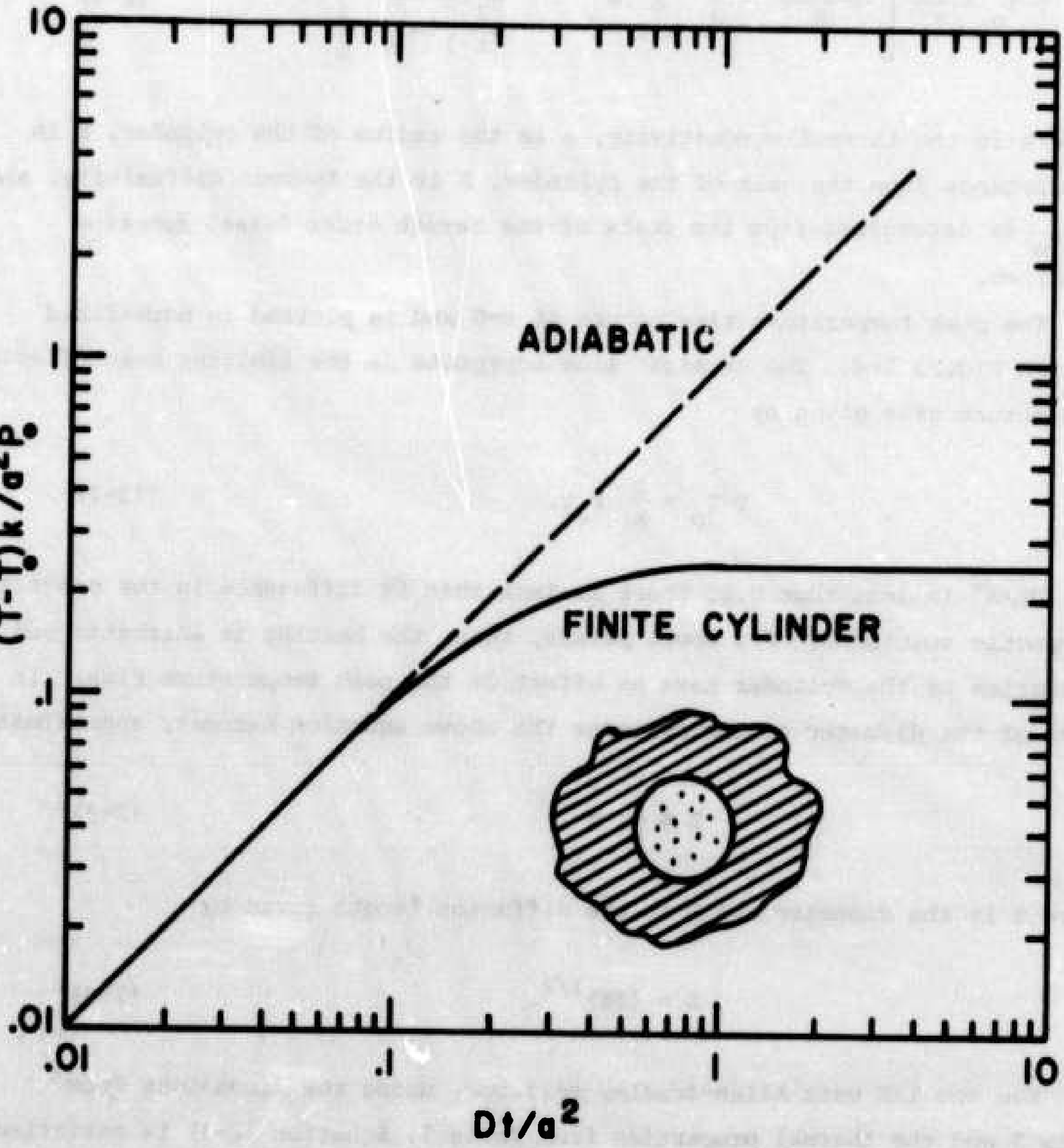


Figure 2-4. Temperature rise at the center of a cylinder with uniform power applied. The solid curve is for a cylinder with radius a imbedded in a perfect heat sink. The dashed line is the case for a very large cylinder or one imbedded in a perfect insulator.

Table 8. Thermal properties of materials used in TRW film-type carbon composition resistors.

	k(watt/cm-°C)	D(cm^2/sec)
Substrate	0.013	0.006
Film	0.25	0.1
Jacket	0.0025	0.001

are those of nearly pure carbon and are much greater than those used for the Allen-Bradley resistors. The decision to use the higher values was a judgment based on the different fabrication techniques. The disparity is not particularly serious, however, since for short pulses the temperature rise is determined by the heat capacity of the carbon, which is nearly the same for both resistor types, while for long pulses the temperature rise is independent of film properties.

The results of computer calculations on temperature distribution are given in Figure 2-5. The curves show normalized peak temperature rise as a function of time for various film thicknesses. The quantity F_o on the ordinate is the area power density in watts/cm^2. Knowing the total power supplied to the resistor and the surface area of the substrate(from Table 5) allows one to calculate F_o. For thick films or very short pulses, the temperature rise is adiabatic and is given by Eq. (2-2). For thin films or for very long pulses, the film can be regarded as infinitesimally thin. In this case, the temperature rise is determined by the properties of the substrate and jacket and is given by[5]

$$T-T_o = \frac{1.128\, F_o \sqrt{D_1\, D_2}}{k_1\sqrt{D_2} + k_2\sqrt{D_1}} \sqrt{t} \qquad (2\text{-}5)$$

where F_o is the area power density and the thermal conductivity and diffusivity are those of the substrate and jacket in either order. Calculations of these two limiting cases show that the temperature is relatively insensitive to

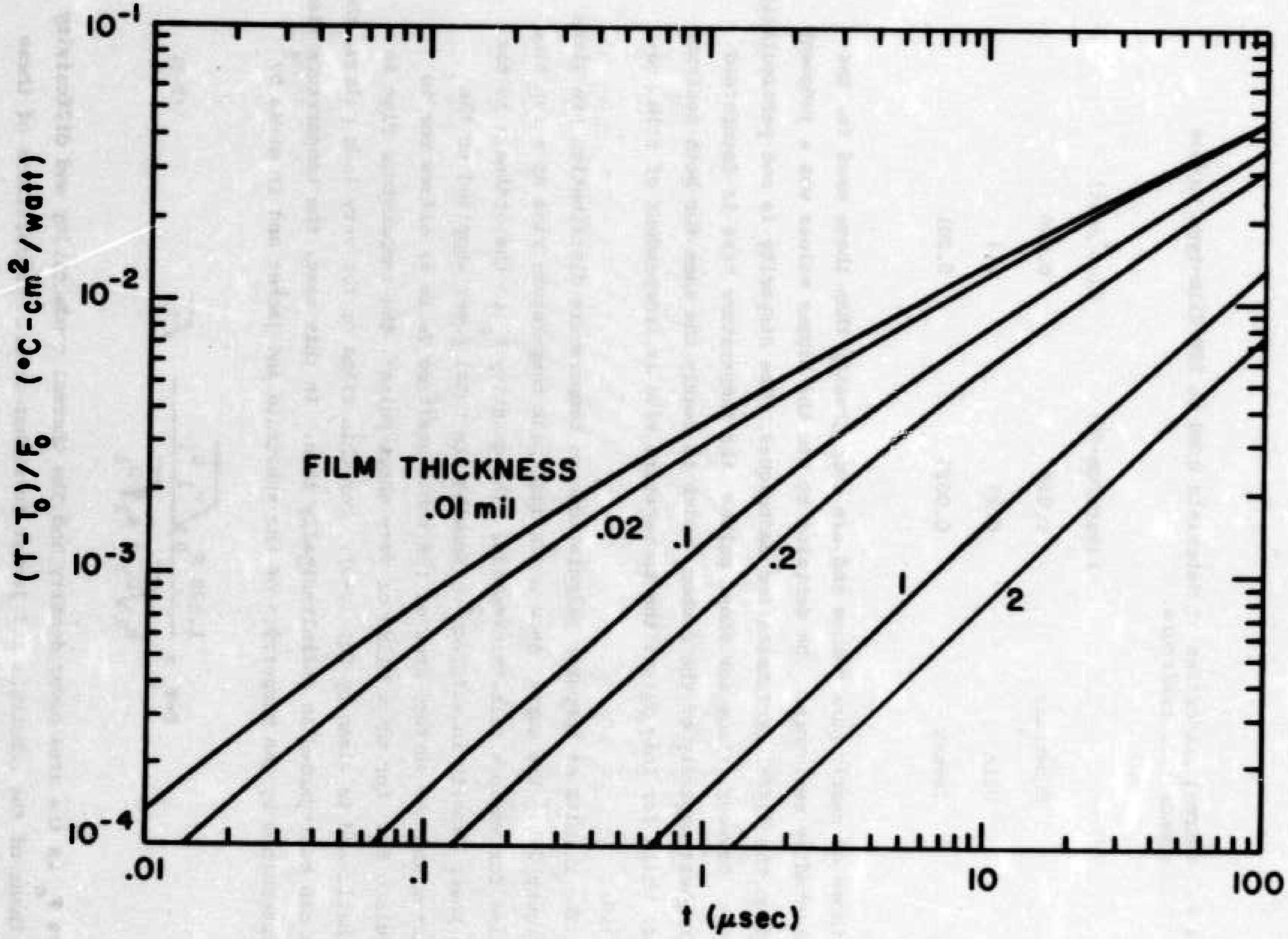


Figure 2-5. Peak temperature rise in a film-type carbon composition resistor.

variations in values of the thermal properties.

In order to give some meaning to the theoretical results just presented, a limited amount of experimental work was undertaken. Several resistor samples were pulse tested to failure in the following manner. First the resistance was measured on a GR 1650A bridge. The resistor was then connected to a Cober 605P pulse generator. A single, constant voltage pulse in the range 1 μsec to 1 msec was applied. Both the voltage and current waveforms were displayed on a dual beam oscilloscope and photographed. The resistance was measured again. If no failure had occurred (failure is defined as a permanent change in resistance to a value outside its tolerance), the pulse amplitude was increased and the procedure repeated.* This was done for several different pulse widths.

The results of pulse testing the Allen-Bradley resistors can be summarized as follows. At low power levels, the voltage and current were constant throughout the pulse, the ratio being the same as the resistance value measured on the bridge. As pulse power increased, the voltage remained nearly constant, but the resistance value decreased slightly, then increased. At sufficiently high power levels, the change in resistance value was permanent and cumulative. For example, a 100 ohm, 1/8 watt resistor had a resistance initially of 99 ohms. After application of a 310 volt, 1 msec pulse, the resistance increased to 101 ohms. After a second pulse the resistance was 105 ohms, after a third, 108 ohms. During the fifth pulse the resistor broke apart. (This overall response was found to be typical of several different resistors tested.)

At high power levels catastrophic failure occurred during a single pulse. The failure was often accompanied by a loud snap and a visible arc. In all but two cases the voltage trace would increase abruptly during the pulse, and the current would decrease correspondingly. It was considerably simpler to define failure for the Allen-Bradley resistors in terms of catastrophic failure rather than a permanent change in resistance greater than the tolerance, and this

---

* A better method is to use a fresh resistor once the threshold power level is reached, since damage is cumulative and the hardness to a pulse depends on the previous history of electro-thermal stress. The procedure here was adopted for expediency.

scheme was adopted. Actually the two threshold levels do not differ significantly anyhow.

Pulse power levels versus time for catastrophic failure are plotted in Figure 2-6. The pulse durations are outside the range of EMP pulses, because the available pulse generator could deliver up to 24 kw only. The data points show little scatter for the 1/8 and 1/4 watt resistors and define straight lines with a slope of -1. This is consistent with a thermal mechanism under adiabatic heating. In such cases, the energy content is independent of pulse time. The data points indicated as "potted" were taken with resistors encased in a clear epoxy potting compound. The significance of this will be pointed out later.

The watt-second energy capability is listed in Table 9 and compared with the advertised value (where the pulse was from a charged capacitor). Also shown is the estimated temperature rise calculated from Eq. (2-2), using dimensions F and G from Table 3 and the thermal properties from Table 7.

Table 9. Pulse handling capability of Allen-Bradley carbon composition resistors.

Size (watts)	Advertised Energy (joules)	Measured Energy (joules)	Peak Temperature (°C)
1/8	0.45	1.4	250
1/4	1.8	4.0	212
1/2	6.4	15	220
1	16		
2	44		

The temperature estimates depend to a large extent on estimates of the thermal and geometric parameters. The peak temperature would be lower, for example, if it were assumed that all of the carbon was uniformly heated - dimension E instead of G in Table 3 (with allowance for the volume of copper leads). However the power distribution is not uniform throughout the resistor, and the use of a smaller equivalent volume tends to correct for this. On the other hand, the calculated peak temperature would be considerably

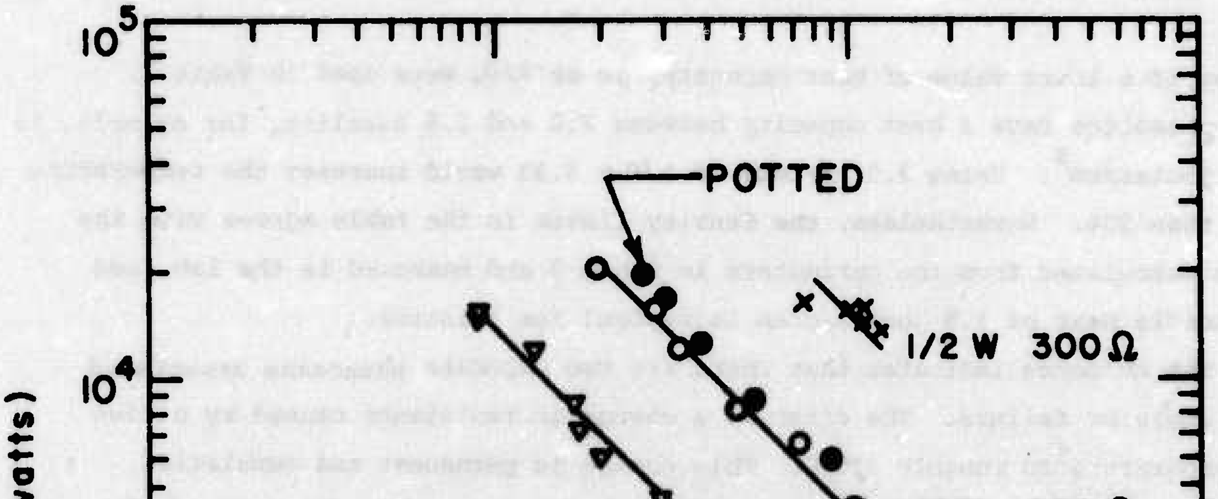


Figure 2-6. Threshold power as a function of pulse width for slug-type carbon composition resistors.

higher if a lower value of heat capacity, ρc or k/D, were used in Table 7. Most phenolics have a heat capacity between 2.0 and 2.6 Bakelite, for example, is 2.03 joules/cm^3. Using 2.5 instead of k/D = 3.33 would increase the temperature more than 30%. Nevertheless, the density listed in the table agrees with the value calculated from the parameters in Table 3 and measured in the lab, and a specific heat of 1.5 joules/gram is typical for plastics.

The evidence indicates that there are two separate phenomena associated with resistor failure. The first is a change in resistance caused by a rise in temperature to roughly 225°C. This change is permanent and cumulative. The second phenomenon is the catastrophic failure caused by fracture of the resistor which is also related to the temperature rise. Attempts to correlate the temperature in Table 9 with the instantaneous resistance from the voltage-current traces by means of published temperature coefficients were unsuccessful. The instantaneous resistance values at the point of catastrophic failure were 25-50% higher than the nominal values, well beyond the range of Figure 2-2.

To substantiate the temperature estimates in Table 9, several resistors were measured and placed in an oven. The resistors were heated, measured, returned to room temperature, and measured again. All the resistors exhibited a temperature coefficient within specifications. After being cycled at relatively low temperatures most of the resistors showed a slight decrease in resistance, probably due to moisture being driven out. After being heated to 200°C for a few minutes, some of the resistors showed a small increase in room temperature resistance. As the soaking temperature was increased above 200°C the room temperature resistance change became more pronounced. When 275°C was reached no stable readings at that temperature could be obtained. The resistance continued to increase at a rate of several percent/minute. After several minutes, the resistors were cooled and were found to have increased by 10 to 50%. Thus it is apparent that the permanent, cumulative changes in resistance during pulse-testing could be caused by high temperature changes in the phenolic above 225°C.

Mechanical failure could be caused by thermal stresses or gas generated by the high temperatures but is otherwise unrelated to the change in resistance value. Five resistors were potted in clear epoxy and then pulsed. In each

case, the power level to cause catastrophic failure was increased by 10 to 30% (see Figure 2-6). Failure was indicated by the voltage-current traces, and by small cracks which appeared in the epoxy.

The discontinuity in the voltage-current waveforms is caused by the fracture in the body of the resistor. This is consistent with all the observed results, including two cases where no discontinuities were noted but the resistors were cracked and showed a significant increase in resistance. This could occur if the resistor remained intact during the pulse, then broke apart due to the mechanical stresses after the pulse was terminated. The maximum voltage available from the pulse generator was 2,500 volts. Since the minimum distance between leads is 90 mils for the 1/8 watt resistor, the maximum voltage gradient in these tests was always less than 30 volts/mil and the possibility of voltage breakdown can be discounted.

To summarize the results on Allen-Bradley resistors the following conclusions can be listed:

1. There is a permanent increase in resistance at temperatures above 225°C.
2. When the increase is produced by pulsed effects, the change cumulative and increases the susceptibility to mechanical failure during succeeding pulses.
3. Catastrophic failure is due to mechanical stresses within the resistor.
4. Threshold power for catastrophic failure follows a 1/t dependence.
5. Voltages in excess of 30 kv are required for voltage breakdown.

Pulsed heating effects are considerably more complicated with the TRW film-type carbon composition resistors. Samples of both finished and uncoated subassemblies of RCR07 (1/4 watt), 1,000 ohm resistors were obtained from the manufacturer. Several resistors of each variety were heated at increasingly higher temperatures for several minutes, then returned to room temperature. At temperatures up to 250°C there was a change of several percent in resistance value, partly recoverable when returned to room temperature. At about 300°C there was a continuous decrease in the resistance of uncoated samples which

was permanent. In molded samples this decrease occurred at 400°C. If the resistors were elevated to still higher temperatures, the decrease was reversed and permanent increases in resistance were noted. This took place near 400°C in uncoated resistors and near 500°C in coated samples. Thus the total change in value of a resistor, either coated or uncoated, depends on its previous history of temperature cycling, including both the temperature reached and its duration.

Bear in mind that the carbon film is baked on at 535°C, although only for a few minutes at most. When some of the resistors were heated to temperatures in excess of this, say 575°C, the film disintegrated and came off the glass substrate. Thus it appears that both the curing temperature and the curing time are important in establishing the final value of resistance. One would expect, then, that during pulse power testing the resistance value might increase or decrease depending upon the exact nature of the thermal pulse. Furthermore, the magnitude of the resistance change would depend on the complete history of heating. Such expectations were borne out during testing.

In Figure 2-7, the results of pulse testing are displayed. Failure was defined as a change in resistance outside the tolerance (5% in this case). Note that there is considerable scatter in the data. Furthermore, the data points show no evidence of a transition from a $t^{-1/2}$ to a t^{-1} dependence.* The fact that the time to failure depends on the power level suggests that the existence of a thermal mechanism is not an unreasonable conclusion, but the lack of definitive asymptotes indicates that more than one mechanism is involved or that a single critical temperature for the initiation of a mechanism does not exist. This supports the previous view that both the temperature excursion and the duration at that temperature determine the final resistance change.

Whenever the resistance decreases with temperature, the current distribution in the film becomes unstable and tends to concentrate in filaments. In semiconductor devices, this phenomena leads to catastrophic failure when the current filament lengthens to bridge the bulk material between contacts.[6] Irregular but well defined tracks were observed on some uncoated resistors during

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*The film is estimated to be about 0.1 mil thick, in which case the transition should occur near 20 μsec. See Figure 2-5.

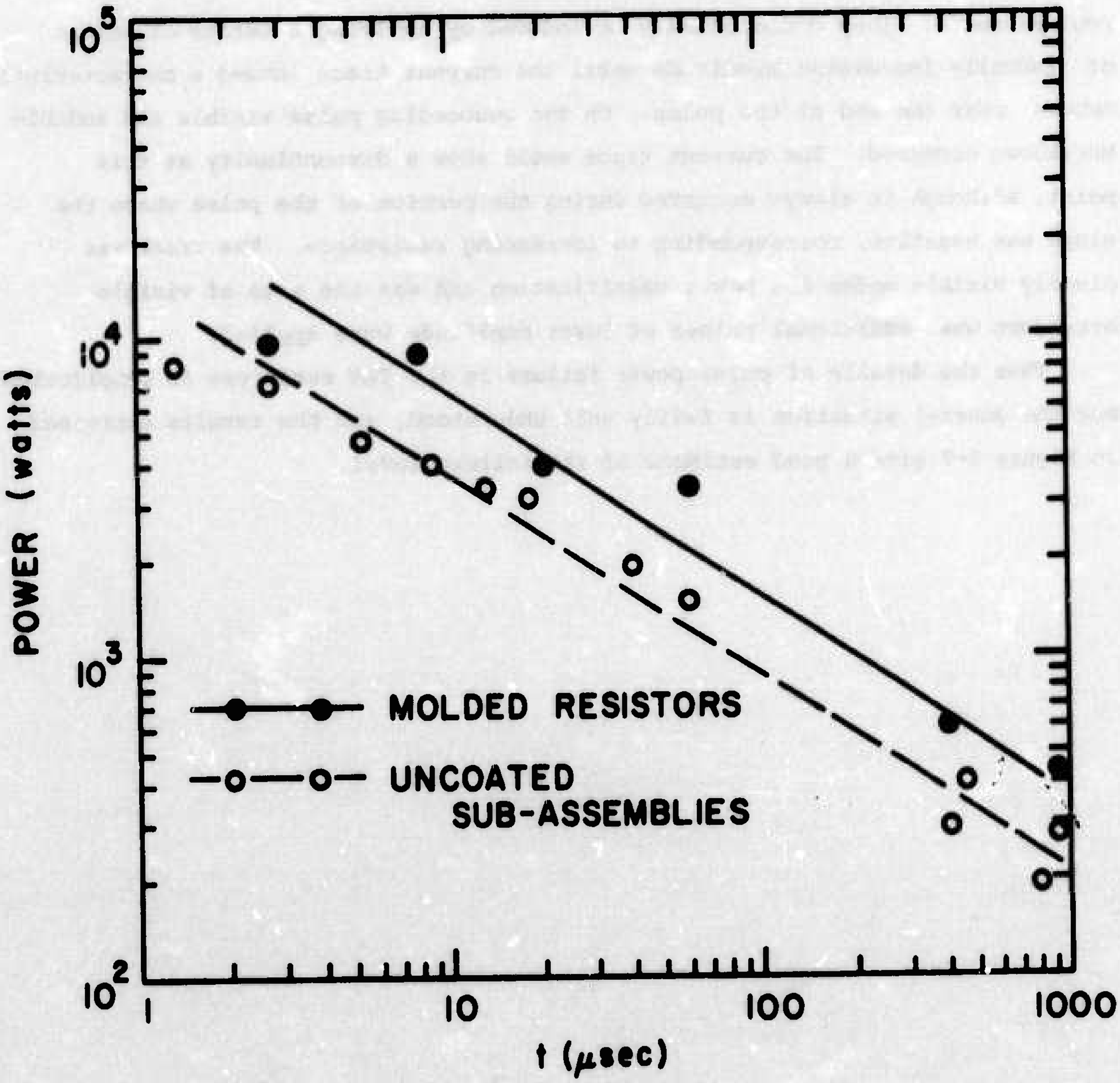


Figure 2-7. Threshold power as a function of pulse width for 1/4 watt, 1000 ohm, film-type carbon composition resistors.

routine tests. They could usually be induced by applying a series of pulses of gradually increasing magnitude until the current trace showed a characteristic upturn near the end of the pulse. On the succeeding pulse visible and audible breakdown occurred. The current trace would show a discontinuity at this point, although it always occurred during the portion of the pulse where the slope was negative, corresponding to increasing resistance. The track was clearly visible under low power magnification and was the site of visible breakdown when additional pulses of lower amplitude were applied.

Thus the details of pulse power failure in the TRW resistors is complicated, but the general situation is fairly well understood, and the results expressed in Figure 2-7 give a good estimate of the failure level.

SECTION III

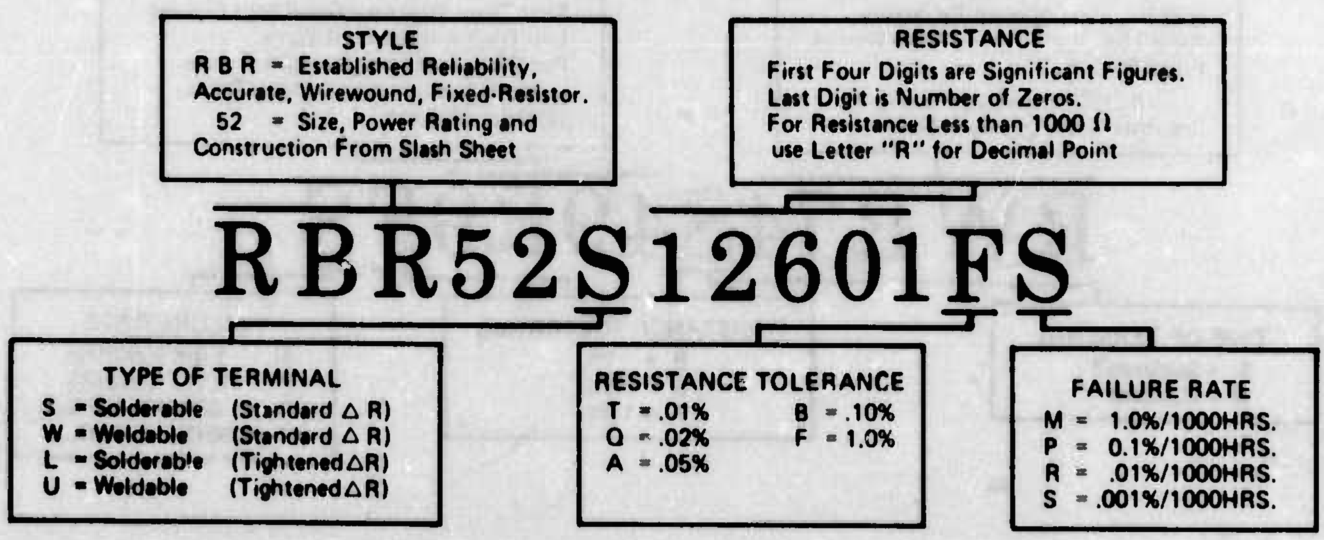
WIRE-WOUND RESISTORS

Wire-wound resistors are generally prescribed where close tolerances and extreme stability are called for. They fall into two broad categories: precision wire-wounds, and power wire-wounds.

Precision wire-wound resistors consist of multiple layers of insulated wire wrapped around an epoxy bobbin having two to eight segments. Adjacent segments are wound in opposite directions in order to reduce the inductance. (This is not what is normally referred to as a non-inductive winding, however, which utilizes an entirely different winding technique.) For low values of resistance the wire is cut to length, then wrapped around the bobbin. For high values of resistance, where wire lengths can easily exceed ten feet, one end of a wire is welded to a lead. The wire is then wound to a pre-determined number of turns, cut, and welded to the other lead. When hundreds of turns are needed, the tolerance is excellent with this method. Monitoring the resistance during winding would be more desirable but is precluded by the insulation on the wire.

Military specifications MIL-R-93 and MIL-R-39005B (established reliability) cover precision wire-wound resistors. The MIL-R-39005B designation is shown in Table 1.

Table 1. MIL-R-39005B designation.



Power wire-wound resistors consist of a single layer of bare wire on a ceramic core. The core is made of steatite, alumina, or beryllium oxide. End caps and leads are fixed to the core, and one end of the resistance wire is welded to a cap. The resistance is measured as the wire is wound on the core and welded to the other end cap at the precise point to achieve the desired resistance value. A ceramic or silicone coating insulates the resistor. Figure 3-1 is a photograph of a power wire-wound resistor made by Ohmite Manufacturing Co.

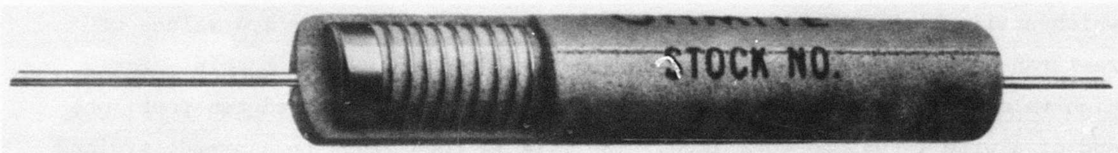


Figure 3-1. Construction details of a power wire-wound resistor.

Power wire-wounds are covered by military specifications MIL-R-26 and MIL-R-39007C. A typical designation is given in Table 2.

Table 2. MIL-R-39007C designation.

STYLE
R W R = Established Reliability, Axial Lead, Power Type, Wire-Wound, Fixed Resistor
74 = Size, Wattage Rating and Construction From Slash Sheet

RESISTANCE
First Three Digits are Significant Figures.
Last Digit is Number of Zeros.
For Resistance Less than 100 Ω, use Letter R to Represent Decimal Point
(49R9 = 49.9 Ω)

RWR74S49R9FS

TYPE OF TERMINAL
S = Solderable
W = Weldable

RESISTANCE TOLERANCE
B = .1%
D = .5%
F = 1.0%

FAILURE RATE
M = 1.0%/1000HRS.
P = 0.1%/1000HRS.
R = .01%/1000HRS.
S = .001%/1000HRS.

More than a dozen companies manufacture wire-wound resistors in this country, dividing up a $60 million dollar market in 1973 - a market expected to grow by 6% a year due to increased demand in consumer electronics. The four largest companies are probably RCL Electronics, Inc., Irvington, New Jersey; Ohmite Manufacturing Co., Skokie, Illinois; Dale Electronics, Inc., Columbus, Nebraska; and TRW, Inc., Philadelphia, Pennsylvania, Boone, North Carolina, and Burlington, Iowa.

RCL Electronics, Inc., manufactures a wide range of both precision and power wire-wounds at its Manchester, New Hampshire, plant. RCL types which qualify under established reliability specifications are listed in Tables 3 and 4.

Table 3. RCL Electronics, Inc., precision wire-wound resistors meeting MIL-R-39005B.

RCL TYPE #	MIL R-39005 TYPE	DIAM. ±.015	LENGTH +.020 −.032	MIL WATT	MAX. VOLTS	MAX. MIL RES.	MILLIMETERS DIAM. ±0.4	MILLIMETERS LENGTH +0.5 −0.8
7009-ER	RBR 56	.250	.344	0.125	150	220 K	6.3	8.7
7010-ER	RBR 55	.250	.500	0.15	200	332 K	6.3	12.7
7020-ER	RBR 54	.250	.750	0.250	300	562 K	6.3	19.05
7030-ER	RBR 53	.375	.750	0.33	400	1.1 Meg.	9.5	19.05
7040-ER	RBR 52	.375	1.000	0.50	600	1.21 Meg.	9.5	25.4

Lead Length: 1½" min #20 AWG (51 + ± 3.2MM) Dia: 0.8 mm

4060-ER	RBR 71	.250 ±.031	.312 ±.031	0.125	150	150 K	6.3 ±0.8	8.0 ±0.8

Standard temp. coefficient ± 20 PPM/°C.
Resistance Tolerances Available: .01%, .02%, .05%, .10%, 1.0%
If solderable leads are required use suffix L.
If weldable leads are required use Suffix U.

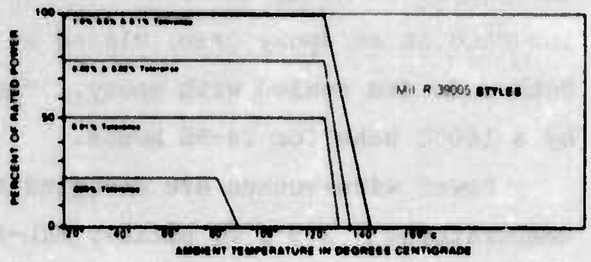
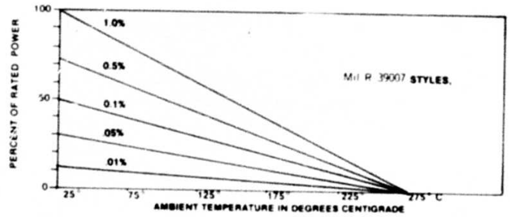


Table 4. RCL Electronics, Inc., power wire-wound resistors meeting MIL-R-39007C.

RCL TYPE #	MIL R 39007 TYPE	DIMENSIONS DIAM. ±.031	LENGTH ±.062	WATTAGE RATING	MAX. RESIS.	LEAD DIAM. AWG	MILLIMETERS	
							DIAM. ±0.8	LENGTH ±1.6
T-2B-71-ER	RWR 71	.188	.812	2.0	16.2K	#20	4.8	20.
T-5-74-ER	RWR 74	.312	.875	5.0	12.1K	#18	8.0	22.2
B-1-ER	RWR 81	.085 ±.020	.250 ±.032	1.0	1K	#24	2.2 ±0.12	2.4 ±0.8
B-3-ER	RWR 80	.094	.406 ±.032	2.0	2.67K	#24	2.4	11.5 ±0.8
B-5-ER	RWR 89	.187	.560	3.0	4.12K	#20	4.8	14.2

Standard temp. coefficient ± 20 PPM/°C.
Resistance Tolerances Available: .1%, .5%, 1.0%
If solderable leads are required use Suffix S.
If weldable leads are required use Suffix W.
Lead length: 1½" minimum.

Non-inductive types MIL approved and available.
Add Suffix N. Divide Max. Resistance Values by 2.



RCL's precision resistors are wound on an epoxy bobbin manufactured by either Maryland Ceramic Corp. or Plasmatex, Inc. The bobbin will deform at temperatures above 180°C, which is somewhat higher than the 145°C maximum temperature specified for the resistors under MIL-R-39007C. After the wire has been wound on the bobbin, it is encapsulated in several different ways. In special cases RTV rubber is used. Usually, the wire is coated with an epoxy. In other cases no coating is used at all. The resistor assembly is inserted in an epoxy case, closed at one end except for a hole for the lead. Both ends are sealed with epoxy. The resistors are then thermally stabilized by a 160°C bake for 24-96 hours.

Power wire-wounds are designed to withstand considerably higher temperatures, 275°C to satisfy MIL-R-39007C. This is the reason for using ceramic cores, single-layer windings, bare wire, and silicone or ceramic coatings. Not only does this eliminate materials incapable of withstanding such temperatures, but provides much higher thermal conductivities so as to achieve higher power densities and smaller packages. At RCL, the resistors

are coated with several layers of a proprietary silicone coating, with each layer cured at 375°C. For unusually severe requirements, special extra processing steps are undertaken which enable the resistors to be operated at red heat (over 1000°C) for a few minutes with very little change in resistance value. These extreme temperatures should be noted, since they have a bearing on the interpretation of pulse-power hardness.

Ohmite Manufacturing Company markets only power type wire-wounds. Two of the popular, low power, axial lead families are the 99 series and the 88 series. The 99 series (Fig. 3-1) is distinguished by an exclusive molded vitreous enamel coating. The coating is able to withstand temperatures up to 820°C. This series is available in four types: 991 and 991R for military applications (MIL-R-26); 994, which is the commercial equivalent of the military types; and 995 which is a commercial, 5% tolerance (10% below 1 ohm) line. Specifications for the 994 type are given in Table 5. These resistors have less than 2% change in resistance value on a 2000 hour, cyclic load-life test.

Table 5. Ohmite 994 type molded vitreous enamel resistor specifications.

3% Tolerance—Tolerances to 0.25% Available

Ohmite Style	Rated Watts @25°C	Dimensions (Inches)			Typical Weight (Grams)	Resistance Range (Ohms)	Max Wkg Volts RMS
		Length ±.015	Dia. +.031 −.000	Leads 1½'' AWG			
994-1A	1.5	.422*	.125*	24	0.4	0.1 to 6650	
994-2A	2.25	.375	.188	20	0.8	0.1 to 6490	85
994-3A	3.25	.547	.203	20	1.3	0.1 to 22,100	190
994-5A	6.5	.922	.312	20	3.6	0.1 to 80,600	460
994-5B	5	.938	.203	20	2.0	0.1 to 53,600	500
994-7A	9	1.218	.312	20	4.5	0.1 to 118,000	670
994-10A	11	1.781	.312	20	6.9	0.1 to 187,000	1100

*Tolerance +.015, −.005

The 88 series has a molded silicone-ceramic jacket and is likewise available in a variety of types: 881 and 881P, meeting military spec MIL-R-26; type 882 for commercial applications; and type 884, the commercial equivalent of the military types. All types have a maximum temperature coefficient of 50 ppm/°C. The specifications of type 884 are listed in Table 6. The standard tolerances are 3%, with tolerances to 0:05% available. Maximum hot spot temperature is 275°C. Average resistance change after 10,000 hours of cyclic load-life testing

is 0.45%

Table 6. Ohmite type 9884 power resistor specifications.

Ohmite Style	Nominal Rated Watts 25°C (1)	Dimensions: Lgth. +.020 −.010	Dia. ±.020	Leads 1½" Long AWG	Typical Weight (Grams)	Resistance Ranges (2): Closer Than 0.5% Tol. (Min. Ohms)	0.5% & Greater (Min. Ohms)	Max. Ohms All Tols	Max. Wkg. Volts RMS
884-1A	1	0.417	0.105	24	0.3	0.499	0.10	7,500	—
884-1B	1	0.542	0.105	24	0.3	0.499	0.10	12,400	—
884-2	2	0.375	0.188	20	0.6	0.499	0.10	7,500	85
884-3 (3)	3	0.542	0.230	20	1.3	0.499	0.10	24,900	200
884-5 (3)	5	0.917	0.323	18	3.3	0.499	0.10	90,900	460
884-7	7	1.218	0.323	18	4.3	0.499	0.10	133,000	670
884-10 (3)	10	1.823	0.343	18	6.3	0.499	0.10	226,000	1100

(1) See derating graph Fig. 18 for ambients above 25°C.

(2) Low resistance values (20 Ω and less) are measured at a point on each lead 3/16" ± 1/16" from body of resistor. Special tolerances to 0.05% can be supplied. For all values 10 ohms and below, it is advisable to use Kelvin bridge technique to eliminate errors due to lead and contact resistance.

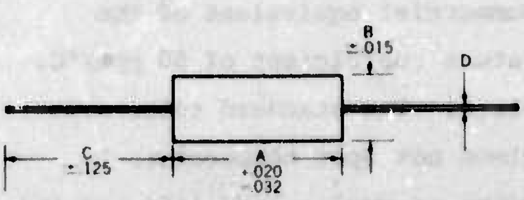
(3) Styles 884-3, 884-5 and 884-10 can be supplied for use as MIL-R-26C Styles RW69G, RW67G and RW68G, respectively. These have better T.C., and stability characteristics than required by MIL-R-26C. The styles supplied under Characteristic P of proposed MIL-R-26D (Bul. 101 or Cat. 50) are furnished under Ohmite Type 881P which is the military equivalent of commercial Type 884.

Dale Electronics, Inc., manufactures a wide variety of both precision and power wire-wounds. Type AWA is designed to meet the requirements of MIL-R-39005B. The standard electrical specifications are given in Table 7, and the dimensions in Table 8.

Table 7. Electrical specifications for DALE AWA type precision wire-wound resistors.

DALE TYPE	MIL-R-39005 TYPE	POWER RATING (WATTS)	MINIMUM RESISTANCE RANGE (OHMS): .01%	.02%	.05%	1%	1%	MAXIMUM RESISTANCE (OHMS) ALL TOLERANCES	MAXIMUM WORKING VOLTAGE	MAXIMUM WEIGHT (GRAMS)
AWA-55	RBR 55	.15	10	10	10	10	.1	250K	200	1.2
AWA-54	RBR 54	.25	10	10	10	10	.1	450K	300	1.5
AWA-53	RBR 53	.33	10	10	10	10	.1	1.1 Meg.	300	3.1
AWA-52	RBR 52	.50	10	10	10	10	.1	1.21 Meg.	600	3.8
AWA-56	RBR 56	.125	10	10	10	10	.1	220K	150	1.0

Table 8. Dimensions of Dale AWA type precision wire-wound resistors.



TYPE	DIM. A	DIM. B	DIM. C	DIM. D
AWA-55	.500	.250	2.000	.032
AWA-54	.750	.250	2.000	.032
AWA-53	.750	.375	2.000	.032
AWA-52	1.000	.375	2.000	.032
AWA-56	.344	.250	2.000	.032

These resistors are epoxy molded, capable of withstanding rated power to 125°C, then derated to zero power at 145°C. Temperature coefficient is 15 ppm/°C maximum. The change in resistance is less than 1% in 2000 hours of load life.

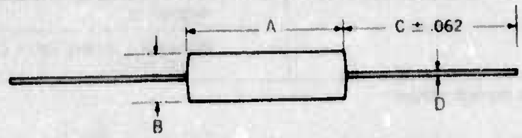
Two groups of power resistors satisfy MIL-R-39007C. The lowest failure rate, 0.01% per 1000 hours, is satisfied by the ARS-AGS type. Electrical specifications are listed in Table 9. These resistors withstand a peak temperature of 275°C and show a resistance change of less than 0.5% in 2000 hours of load life.

Table 9. Electrical specifications of Dale ARS-AGS type power wire-wound resistors.

DALE TYPE	MIL-R-39007 TYPE	DALE POWER RATING (Watts)	MINIMUM RESISTANCE (Ohms)	MAX. RESISTANCE (Ohms)	MAX. WORKING VOLTAGE	MAX. WEIGHT (Grams)	DIM. A	DIM. B	DIM. C	DIM. D
*AGS-1	RWR-81	1	0.1	1.0K	25	.35	.276 ± .005	.100 ± .005	1.5	.020
AGS-2	RWR-82	1.5	0.1	1.3K	32	.30	.312 ± .016	.078 ± .031	1.5	.020
**AGS-3	RWR-80	2.25	0.1	2.67K	52	.375	.426 ± .005	.120 ± .005	1.5	.020
AGS-5	RWR-89	4	0.1	4.12K	112	1.25	.560 ± .062	.187 ± .031	1.5	.032
AGS-10	RWR-84	7	0.1	12.4K	275	4.25	.875 ± .062	.312 ± .031	2.0	.040
ARS-2	RWR-71	2	0.1	16.2K	180	1.6	.812 ± .062	.187 ± .031	1.5	.032
ARS-5	RWR-74	5	0.1	12.1K	250	4.75	.875 ± .062	.312 ± .031	2.0	.040
ARS-10	RWR-78	10	0.1	40K	650	12.00	1.780 ± .062	.375 ± .031	2.0	.040
**AGS-1-118	RWR-81N	1	10.0	499	17	.35	.276 ± .005	.100 ± .005	1.5	.020
AGS-2-118	N.A.	1.5	10.0	650	22	.30	.312 ± .016	.078 ± .031	1.5	.020
**AGS-3-118	RWR-80N	2.25	10.0	1.33K	36	.375	.426 ± .005	.120 ± .005	1.5	.020
AGS-5-118	RWR-89N	4	10.0	2.05K	75	1.25	.560 ± .062	.187 ± .031	1.5	.032
AGS-10-118	RWR-84N	7	10.0	6.19K	190	4.25	.875 ± .062	.312 ± .031	2.0	.040
ARS-2-118	RWR-71N	2	10.0	8.06K	125	1.6	.812 ± .062	.187 ± .031	1.5	.032
ARS-5-118	RWR-74N	5	10.0	6.04K	175	4.75	.875 ± .062	.312 ± .031	2.0	.040
ARS-10-118	RWR-78N	10	10.0	19.6K	450	12.00	1.780 ± .062	.375 ± .031	2.0	.040

*Consult factory for extended values.
**Molded model.

Tolerance: All established reliability resistors have a standard resistance tolerance of 1%.



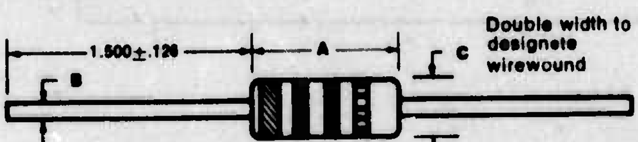
The ARS resistors are fabricated on an alumina core, with stainless steel end caps and tinned nickel leads. The AGS series uses a beryllium oxide core which, because of its higher thermal conductivity, has a higher dissipation for a given size. Both series of resistors are available in either a silicone coated or molded jacket. The AGS series has achieved a failure rate of 0.000032% per 1000 hours at the 60% confidence level under 50% power, 25°C ambient. (Failure is defined as a resistance change greater than 0.5%.)

TRW manufactures a variety of wire-wound resistors at several plant locations. Samples of a commercial type from the Philadelphia plant were obtained from AFWL. These are designated the BW-20 style (1 watt) and the BWH style (2 watts). They are not covered by any current military specification. The electrical specifications are listed in Table 10.

Table 10. Electrical specifications for TRW general purpose, molded wire-wound resistors.

TRW TYPE	BW-20	BWH
EIA RS-344 Style	CRU1	CRU2
MIL-R-11 Style Size Equivalent	RC20	RC32
Resistance, Standard	0.24 Ohms thru 750 Ohms*	0.10 Ohms thru 2400 Ohms*
Tolerance, Standard Special	±5%, ±10% ±2%	±5%, ±10%
Power Rating	1-watt 50°C ½-watt 100°C ¼-watt 125°C, derating to 0 ● 160°C	2-watts ● 70°C 1-watt ● 115°C ½-watt ● 137°C, derating to 0 ● 160°C
Max. Continuous Working Voltage	✓ PR	✓ PR
Min. Insulation Resistance—Dry	10,000 Megohms	10,000 Megohms
Min. Insulation Resistance—Wet	100 Megohms	100 Megohms
Min. Dielectric Withstanding Voltage Atmospheric Pressure Reduced Pressure	 700 Volts, R.M.S. 450 Volts, R.M.S.	 1000 Volts, R.M.S. 025 Volts, R.M.S.
Hot Spot Temp. Rise at 1-Watt	100°C	115°C
Current Noise	Negligible	Negligible
Marking	Standard EIA/MIL Color Code (double width first band)	Standard EIA/MIL Color Code (double width first band)

*See page 7 for decade values



	A	B	C
BW-20	.390 ± .010	.032 ± .001	.140 ± .008
BWH	.562 ± .010	.040 ± .001	.225 ± .008

The core of these resistors is a fiberglass cord impregnated with silicone. The length of the core is the same for all resistors of one style with the resistance value being determined by the size and type of wire and the pitch of the winding. For the BW-20 types, the active core length is 155 mils. The core diameter is adjusted slightly so that the outside diameter of the winding is held at 51 mils. The pitch varies from about 50 to 600 turns per inch. In the BWH series the active core length is 250 mils, with an outside diameter of 75 mils. The pitch is 30-450 turns per inch. End caps and leads (single-piece construction, tin/lead coated, nickel plated copper leads, BW-20 style; leads with brass end caps, BWH style) are welded or crimped on. From this point on, the processing is the same as for carbon composition resistors, GBT-1/2 and GBT-1 styles. The jacket is compression-molded phenolic. Standard color coding is used except that the first band is extra wide to distinguish wire-wound from carbon composition resistors.

No temperature cycling is used to stabilize the resistance other than the 350°C, 1 minute cycle encountered during the final molding operation. Consequently the temperature coefficient is rather large, up to 0.08% per °C. The resistors can dissipate full rated power to 50°C (70°C for BWH style), derated to zero at 160°C. Change in resistance is less than 3% (5% for BWH style) over the load life.

One material which both precision and power wire-wounds have in common is the resistance wire. More than two dozen companies, domestic and foreign, produce resistor alloys. Only three of these companies will be discussed here. Together they supply probably 90% of the domestic market. These companies are: Wilbur B. Driver Company, Newark, New Jersey; Driver-Harris Company, Harrison, New Jersey; and Molecu-Wire Corporation, Farmingdale, New Jersey.

Resistance wire falls into several distinct categories based on composition. The most important of these are the high-resistivity nickel-chromium alloys and the copper-base alloys. The most common are listed in Table 11.

The resistivity tolerance on alloy wire is typically 10%, caused by variations in melt composition and in the heat treatment before and after drawing. The resistance variation for a given spool of wire, however, is much less than this, usually a fraction of 1%. This makes it possible to calculate beforehand the required lengths of wire for precision wire-wounds.

Table 11. Properties of resistance wire.

Manufacturer	Tradename	Composition	Resistivity: Ohms per circular mil foot	Resistivity: Microhm centimeters	Temperature Coefficient of resistivity: ppm/°C	Temperature Coefficient of resistivity: Range, °C	Specific heat calories/gram °C
1. Wilbur B. Driver	Evanohm	75Ni, 20Cr, Bal Al, Cu	800	133	± 5	-65 to 125	.107
2. Driver-Harris	Karma	73Ni, 20 Cr, Bal Al, Fe	800	133	± 20	-50 to 105	.104
3. Molecu-Wire	Moleculoy	75Ni, 20 Cr, 3Al, 2Co	800	133	± 5	-65 to 150	.104
4. Wilbur B. Driver	Cupron	55Cu, 45Ni	300	50	± 40	25 to 105	.094
5. Driver-Harris	Advance	57Cu, 43Ni	294	49	± 20	20 to 100	.094
6. Molecu-Wire	Neutroloy	55Cu, 45 Ni	300	50	± 10	-65 to 150	.094
7. All	Manganin	86-83Cu, 10-13Mn,	290	48.2	± 15	15 to 35	.097

	Thermal conductivity watts/cm-°C	Specific gravity	Melting point °C	Maximum operating temperature °C
1.	.152	8.1	1350	350°C*
2.	.130	8.11	1400	----
3.	.131	8.12	1395	250°C
4.	.212	8.9	1210	538°C
5.	.212	8.9	1210	----
6.	.218	8.9	1210	550°C
7.	.264	8.4	1020	60°C

*The manufacturer suggests 316°C, however 350°C is the requirement of MIL-R-26, characteristics P, R, and V. Many lines of resistors, including some discussed here, meet this requirement. Consequently, the calculations to follow are based on the higher temperature.

Wire sizes range from 0.28 mils to 410 mils in diameter, but 0.5 to 10 mils is commonly used. Rods and ribbon are also available. Wire can be supplied bare, for power wire-wounds, or coated with various enamels, plastics, or fabrics in single or multiple layers. Enameled wire is most commonly used for applications requiring insulated wire. A layer of enamel will increase the wire diameter by 0.1 to 1.6 mils.

When a wire is wound onto a bobbin or core, the radius of the substrate is important. Some manufacturers recommend a minimum diameter for the bobbin depending on the wire size and the winding tension. Heavy wire sizes require larger bobbins. Increased winding tension likewise requires larger bobbins. Otherwise, mechanical stresses are set up which can cause small changes in electrical properties.

Some consideration must be given to the material comprising the bobbin or core. If the temperature coefficient of expansion of the substrate does not match that of the wire, unequal expansion will occur during operation. This in turn will magnify the temperature coefficient of resistance.

When a nickel-chromium wire is placed under tension, the resistivity of the material decreases and the temperature coefficient increases. The tension also causes a slight decrease in diameter, however, which more than compensates for the resistivity decrease so that the resistance per foot increases. Pure bending strains, on the other hand, involve zero dimensional changes so that the net change in resistance caused by bending is positive. The winding operation introduces both tension and bending strain. The change in resistance over a period of time reflects the relief of winding stresses during the aging process.

For maximum stability of the finished product, the resistors are annealed to relieve winding-induced stresses. The baking temperatures range from 120°C to 160°C for precision resistors. This is limited by the epoxies and enamels used in construction. Annealing times vary from 24 to 96 hours, with longer times required where maximum stability is called for. Power wire-wounds can be baked at significantly higher temperatures, say 350°C, since the materials can withstand higher temperatures and the resistors themselves must be capable of sustained operation at hot spot temperatures of either 275°C or 350°C, depending on the military specification.

In fabricating a particular resistor, for example, 1000 ohms, 1 watt, almost any combination of wire size and length can be used, in principle. If 1 mil Evanohm were selected, the resistance would be 800 ohms per foot and the resistor would require 1.25 feet of wire. If the wire diameter were 5 mils, the length would need to be 31.25 feet. Certain practical considerations restrict the range of choices, however.

In a power wire-wound, it is essential to provide good thermal contact between the wire and the substrate and jacket. This is the reason that bare wire is used since enamel is a poor heat conductor. The longer the wire the better the thermal contact. The number of turns is limited, however, by the need for adequate spacing between turns to minimize the possibility of short-circuiting adjacent turns or of arcing between turns. This, together with requirements on minimum wire diameter and overall resistor size imposed by the military specifications, dictates a restricted range of choices for wire size and length. In practice, power wire-wounds typically contain about 1 foot of wire - longer at high values of resistor, shorter at low values.

Precision wire-wounds, on the other hand, contain much longer lengths - 25 feet is not uncommon for resistors of several thousand ohms. Power densities are relatively low. In the first place, the temperature excursion is restricted, and secondly the thermal resistance of the materials - enamels, epoxies, RTV rubber, etc. - is high. The primary purpose of the precision wire-wound is to provide accurate, stable resistance, and this is best achieved by a longer length of wire.

Evanohm and the other nickel-chromium alloys are used for the higher resistance ranges, say above 100 ohms, while Cupron and other copper-based alloys are used for low ranges. At very low values of resistance, ribbon or strip is used. Manganin is not utilized at all in power resistors due to its limited temperature range.

The transient temperature rise during an EMP pulse is more difficult to determine for wire-wound resistors than for carbon composition resistors. The small diameter and high thermal diffusivity of the wire allow considerable heat transport to the surrounding material during a 100 μsec pulse. For

example, in low resistance power resistors Cupron wire from 10 mils to 3 mils is common. Employing the criterion from Section II (Eq. 2-3), the boundaries of a 3 mil wire can be ignored for periods up to 25 μsec. When Evanohm is used, where wire sizes from 0.3 to 5 mils are common, the upper limit for adiabatic heating of fine wires is 1 μsec.

For precision wire-wounds, the wire sizes are even smaller. The enamel coating on the wire does provide a thermal barrier, however, so the heat diffusion into the surrounding material can sometimes be neglected even for long EMP pulses.

In lieu of more exact calculations on temperature distributions which can account for thermal transport into adjacent materials, the adiabatic approximation can be used to provide simple, conservative, order-of-magnitude answers to thermal problems in wire-wounds. In this case the temperature rise of the wire is given by

$$T-T_o = \frac{DPt}{k} = \frac{4}{\pi} \frac{DE}{k\,d^2 L} \tag{3-1}$$

where E is the energy of the pulse, d is the wire diameter, and L is the wire length. Using the thermal properties from Table 11 and the maximum allowable temperatures listed there (with $T_o = 20°C$), one can solve for the energy required to reach the maximum temperature. The results are

$$E = 0.28\, d^2 L \quad \text{(Cupron)} \tag{3-2}$$

$$E = 0.19\, d^2 L \quad \text{(Evanohm)} \tag{3-3}$$

where E is in joules, d is in mils, and L is in feet.

As pointed out earlier, for a given power rating and resistance value some variation in wire sizes and lengths is possible. The energy calculated from Eqs. (3-2) or (3-3) is not independent of this choice. That is to say, if the diameter is increased then the length must simultaneously be increased to maintain the same resistance value, and both effects increase the threshold energy. Values of energy can be calculated only if two of three quantities are known: d, L, and resistance value.

Two manufacturers supplied winding tables for some of their power resistor styles. Starting from the lowest value of resistance and largest wire size, increasing values of resistance incorporate increasing lengths of wire. At some value of resistance, a change is made to a smaller wire size and a shorter length. The same size is employed throughout the next resistor range. For example, one manufacturer uses 5 mil Cupron in the range 1.12-1.50 ohms, 4.5 mils in the range 1.50-2.18 ohms, etc.

This information makes it possible to calculate E as a function of resistance. When the function is plotted, a sequence of discontinuous segments for each power rating results. Each segment corresponds to a particular wire size and resistance range. When a single curve is fitted to the sequence it is found that a simple functional relationship exists, namely,

$$E = \frac{A}{R^{1/3}} \qquad (3\text{-}4)$$

where A is a constant which depends on the power rating, R is the resistance in ohms, and E is the pulse threshold energy in joules. These relationships are illustrated in Figure 3-2. Values for the constant A are given in Table 12.

Table 12. Coefficients for predicting threshold energies.

Military designation	Rating (watts)	A
RWR81	1	1.0
RWR82	1 1/2	1.4
RWR80	2	3.5
RWR89	3	13
RWR84	7	73
RWR78	10	320

Equation (3-4) predicts within a factor of two the energy required to reach the maximum allowable temperature for either Evanohm or Cupron. It holds for resistors from two manufacturers. The equation is valid for resistance ranges from about 1 ohm to 1,000 ohms for 1 watt sizes, and

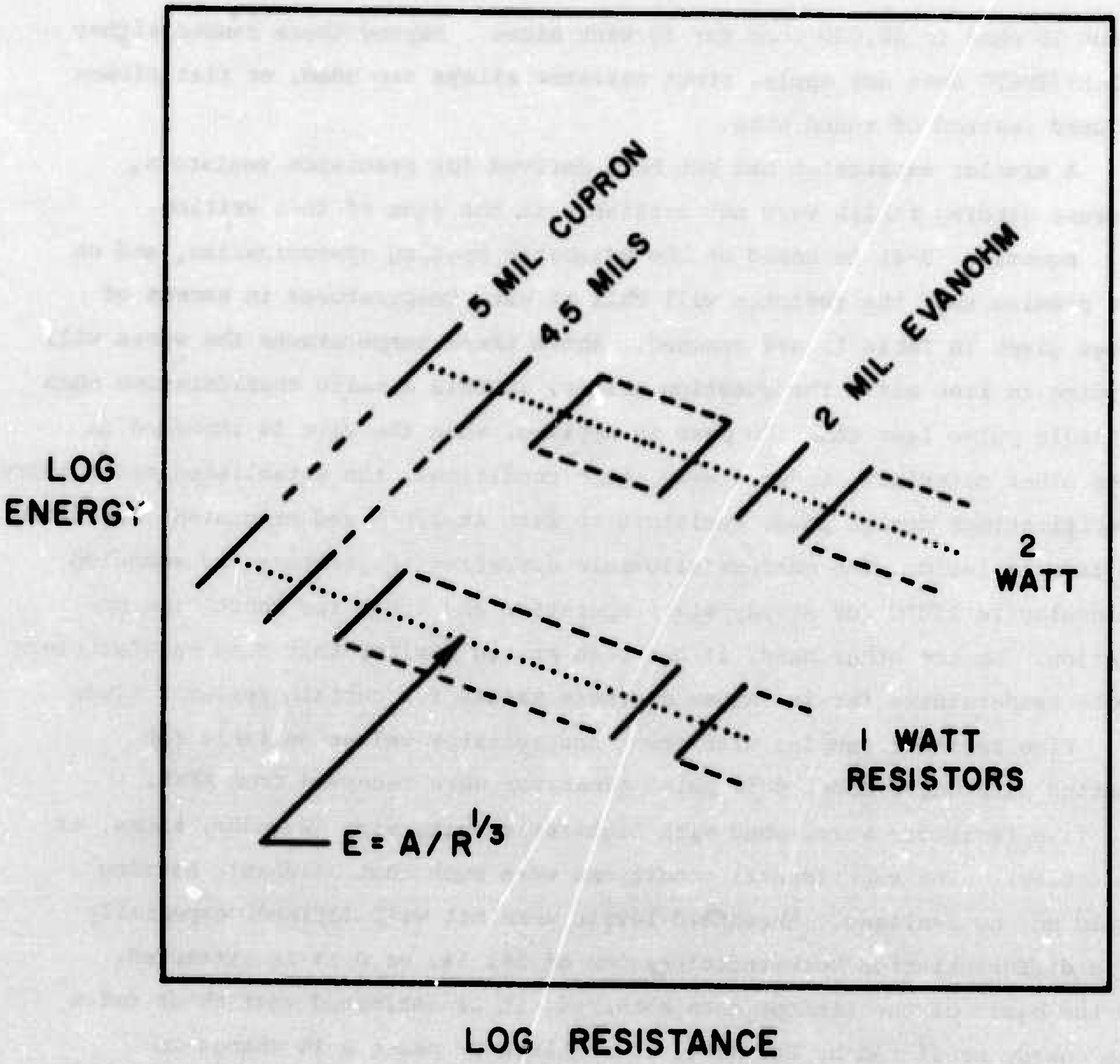


Figure 3-2. Energy versus resistance curves for wire-wound resistors.

about 10 ohms to 40,000 ohms for 10 watt sizes. Beyond these ranges either MIL-R-39007C does not apply, other resistor alloys are used, or flat ribbon is used instead of round wire.

A similar expression has not been derived for precision resistors, because winding tables were not available at the time of this writing.

Equation (3-4) is based on the adiabatic heating approximation, and on the premise that the resistor will fail if wire temperatures in excess of those given in Table 11 are reached. Above these temperatures the wires will oxidize in free air. The question arises, is this a valid consideration when a single pulse less than 100 μsec is applied, when the wire is imbedded in some other material? Under steady state conditions, the established reliability specifications derate power resistors to zero at 275°C and precision resistors to zero at 145°C. The maximum allowable operating temperature for enameled Moleculoy is 250°C for steady state operation and 450°C for short time operation. On the other hand, it has been stated earlier that some manufacturers quote temperatures far in excess of these values for certain resistor types.

Five resistor samples with power and resistor values suitable for testing on a Cober Model 605P pulse generator were received from AFWL. All five resistors were wound with high-resistivity wire (Evanohm, Karma, or Moleculoy). The experimental conditions were such that adiabatic heating could not be realized. Threshold levels were not well defined, especially if a differentiation between tolerances of 5%, 1%, or 0.1% is attempted. On the basis of the limited data obtained, it is estimated that about twice the energy predicted by Eq. (3-4) is required to cause a 1% change in resistance, and about four times the energy will cause catastrophic failure. Prior to catastrophic failure the resistance changed by as much as 10%. On this basis, peak temperatures of 700°C must be reached to cause a 1% change in these resistors, and catastrophic failure occurs only when the temperature reaches the melting point of the wire. Note that for resistors wound with Cupron or equivalent, energies only about 2 1/2 greater than that given by Eq. (3-4) will cause melting.

SECTION IV

CARBON FILM RESISTORS

Carbon film resistors are fabricated by the pyrolytic deposition of carbon on the hot surface of a ceramic substrate. The source of the carbon is an organic gas, such as methane, which is cracked at a temperature of 1100°C. Film thicknesses range from less than 0.1 mil on up to 3 mils. The thinnest films have sheet resistivities of 10,000 ohms per square and exhibit the highest temperature coefficient, -700 ppm/°C. Thicker films have resistivities as low as 10 ohms per square and temperature coefficients of -200 ppm/°C. Contacts are made to the carbon film by force-fitted end caps, with a layer of silver cement for better contact. The resistors are spiralled and a jacket applied. The jacket can be either a thermosetting resin, a conformal coating, a molded epoxy, or a ceramic coating.

Apart from special purpose products, carbon film resistors are available in sizes from 1 watt to 5 watts and resistance ranges from 1 ohm to 20 megohms, .5%, 1%, 2%, and 5% tolerances. Advertised temperature coefficients range from +200 to -2500 ppm/°C. It is the only type of resistor featuring a negative temperature coefficient.

Comparatively few companies make carbon film resistors in this country. Products from three companies were studied: Dale Electronics, Inc., Norfolk, Nebraska; Mepco/Electra, Inc., Morristown, New Jersey; and Ohmite Manufacturing Co., Skokie, Illinois. The latter two companies are subsidiaries of North American Phillips and market nearly identical carbon film resistors. The relevant military specification for products of these three companies is MIL-R-10509.

Dale produces four series of carbon film resistors including a high voltage type and a hermetically sealed line. The remaining two types are identical except that one has a molded jacket and the other has a conformal coating. The resistors are fabricated in the manner previously described. The standard cap and lead assembly is solder coated copper although nickel, gold-plated Dumet, or other special alloys are available. The MC series has a molded epoxy jacket while the DC series uses a conformal epoxy coating. The units which were received by Clarkson were all uncoated, 1/10 to 2 watt

sizes, 10 to 50 ohms. They either had no spiral cuts or less than one complete revolution.

The standard electrical specifications are given in Table 1 for the MC series. The DC series is similar except that a 5W size is also available. Both series have an operating temperature range from -55 to 165°C. Power ratings in Table 1 are based on a 1% maximum change in resistance in 1000 hours of load life at 70°C ambient. Above 70°C the dissipation must be derated to zero at 165°C.

Table 1. Electrical specifications of Dale series MC carbon film resistors.

DALE TYPE	MIL.* TYPE	POWER RATING (WATTS)		MINIMUM RESISTANCE (OHMS)	MAXIMUM 1% RESISTANCE (OHMS)	MAXIMUM 2% RESISTANCE (OHMS)	MAX. WT. (GRAMS)	MAX. WORKING VOLTAGE
		[illegible]	[illegible]					
MC-1/10	RN 55	1/10	1/8	1	400K	400K	.35	200
MC-1/8	RN 60	1/8	1/4	1	3 Megohms	5 Megohms	.45	300
MC-1/4	RN 65	1/4	1/2	1	5 Megohms	6 Megohms	.85	350
MCS-1/2	RN 70	1/2	3/4	1	10 Megohms	15 Megohms	1.50	500
MC-1	RN 75	1	—	1	15 Megohms	30 Megohms	4.50	500
MC-2	RN 80	2	—	2	100 Megohms	125 Megohms	8.25	750

Tolerance .5%, 1%, 2% *Reference only. No QPL's are maintained.

Typical temperature coefficient curves, valid for either series, are given in Figure 4-1.

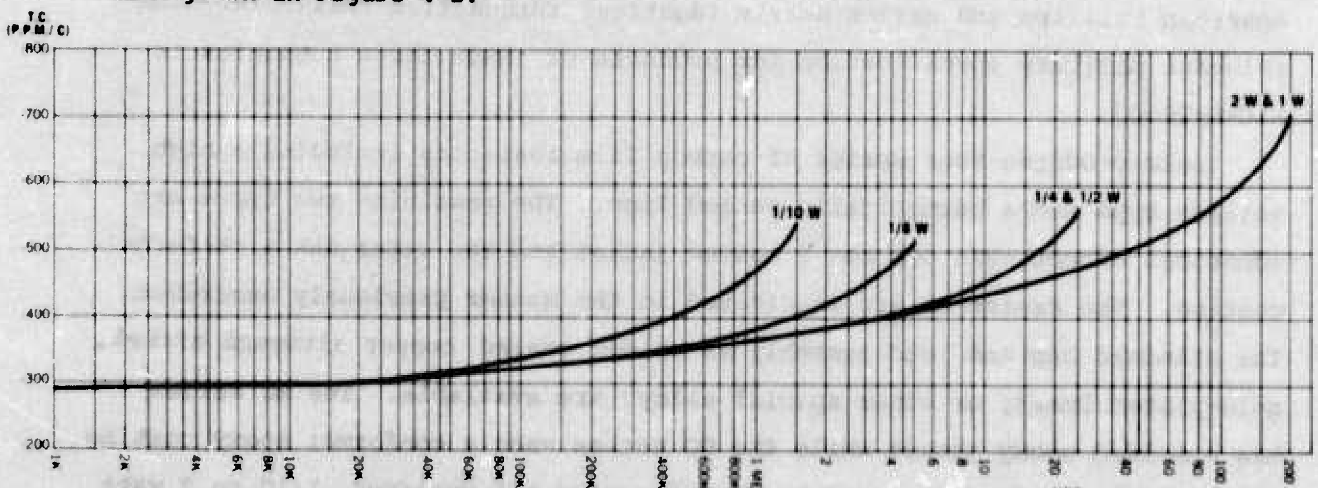


Figure 4-1. Typical temperature coefficients for Dale carbon film resistors.

Surface temperature rise above ambient is shown in Figure 4-2. The two separate values are for the B and D characteristics of MIL-R-10509. Conformal coated resistors have a somewhat higher surface temperature due to the thinner jacket, up to 90°C for the 2 watt and 5 watt resistors.

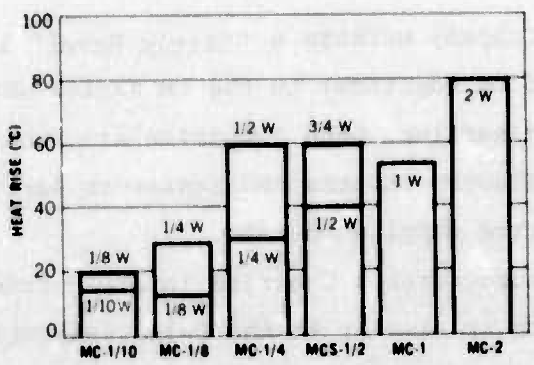


Figure 4-2. Surface temperature rise above ambient for Dale MC carbon film resistors.

The dimensions of the MC series, in inches, are listed in Table 2.

Table 2. Dimensions in inches of Dale MC carbon film resistors. All leads are 1.5 inches long.

Dale type	Body length	Body diameter	Lead diameter	Film length
MC-1/10	o.26	0.095	0.025	0.1
MC-1/8	0.406	0.135	0.025	0.27
MC-1/4	0.593	0.203	0.025	0.312
MCS-1/2	0.73	0.250	0.032	-----
MC-1	1.093	0.375	0.032	-----
MC-2	2.188	0.375	0.032	1.65

The substrate length is slightly smaller than dimension A. The last column in the table is the length of active film, that is, the distance between the silver end contacts. Conformally coated resistors have a maximum diameter slightly less than dimension B. The 5 watt resistor has a length of 4.00 inches, a diameter of 0.438 inches, and a lead diameter of 40 mils.

Ohmite Manufacturing Company markets a "Little Rebel" line of carbon film resistors. These appear to be identical to the CR series obtainable from Mepco/Electra, Inc. As mentioned earlier, both companies are subsidiaries of North American Phillips. Mepco/Electra imports the resistors for their CR series, and apparently the same source supplies Ohmite.

Mepco/Electra also manufactures a C series in its Morristown, New Jersey, plant. Construction is similar to the Dale resistors. There is both a military grade, meeting MIL-R-10509, and an industrial grade. They are identical except that the military styles are hermetically sealed in a ceramic jacket while the industrial styles are coated with several layers of a proprietary synthetic resin. In addition, the industrial line includes a 1/10 watt resistor. A cutaway view of a military style resistor is shown in Figure 4-3.

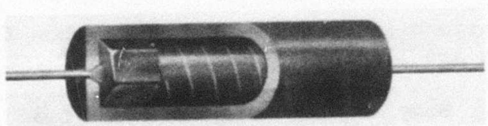


Figure 4-3. Mepco/Electra C series military style hermetically sealed carbon film resistor.

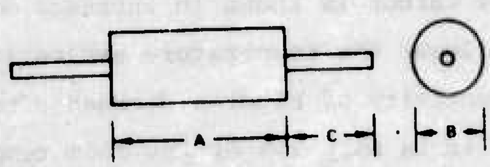
The electrical specifications and dimensions are given in Table 3. The temperature coefficient for these military style resistors is advertised as +200 to -500 ppm/°C. The power dissipation is for ambient temperatures up to 70°C, derated linearly to 150°C (characteristic B, MIL-R-10509). The change in resistance is less than 0.5% after 1000 hours of full load life at 20°C for resistors less than 10,000 ohms. For high values of resistance, hence for very thin films, the resistance change can be 4% or more.

Table 3. Electrical specifications and dimensions for Mepco/Electra C series military style carbon film resistors.

Mepco-Electra Type	MIL Type	MIL Power Rating (70°C)	Resistance Range* (ohms)	Resistance Tolerance	Max. Voltage (Volts)	Dimensions (inches black, centimeters white) — see diagram: A	B	C (AWG)	CL-CL** (Max.)
C170N	RN60G	1/8W	5Ω–1Meg	±1%	250	.433±.003	.155±.010	1.5 (#22)	.498
C173C	RN65G	1/4W	10Ω–2Meg	±1%	300	.640±.015	.244±.005	1.5 (#22)	.704
C173BN	RN70G	1/2W	10Ω–5Meg.	±1%	350	.825±.017	.250±.010	1.5 (#20)	.889
C177AN	RN75G	1W	10Ω–5.11Meg.	±1%	500	1.093±.020	.395±.020	1.5 (#20)	1.157
C177BN	RN80G	2W	30Ω–20Meg	±1%	750	2.250±.025	.395±.020	1.5 (#20)	2.314

*Within the resistance ranges shown, resistance values indicated in the MIL 10 to 100 decade table of values (see Table page 43), and their decade multiples, are available as standard. Other values are available on special order.

**Clean-lead to clean-lead.



Samples for this particular line of resistors were not received, so substrate dimensions are not known. It is known that the substrates are of high grade alumina.

When a single power pulse is applied to a carbon film resistor, heat generated in the film causes an increase in temperature that can lead to permanent degradation, ignoring for the moment the possibility of voltage breakdown. The principles of heat transfer and methods of analysis of film resistors are described elsewhere[1]. The thermal properties of the

materials for carbon film resistors are listed in Table 4.

Table 4. Properties of materials for carbon film resistors.

		Thermal conductivity watt/cm-°C	Diffusivity cm^2/sec
substrate	(alumina)	0.25	0.08
film	(carbon)	0.20	0.10
jacket	(epoxy)	0.0025	0.001

Computer calculations for the peak temperature rise in the carbon film, based on the properties in Table 4, are shown in Figure 4-4. The ordinate in the figure is temperature rise per unit surface power density. For the 3 mil film, the temperature rise is adiabatic over nearly the whole range of EMP pulse lengths. For the 0.03 mil film, the solution over most of the range approximates that of an infinitesimally thin film.

The computer solutions depend to a great extent on the heat capacity of the film and on the thermal properties of the substrate. The solutions in Figure 4-4 utilize the room temperature properties of the materials as listed in Table 4. The specific heat of carbon is known to increase somewhat with temperature. This would tend to lower the temperature estimates slightly. On the other hand, the thermal conductivity of alumina decreases rather drastically with temperature, until at 800°C it is only 25% of the room temperature value. This would tend to raise the peak temperatures by a considerable amount. Beryllium oxide has nearly ten times the thermal conductivity of alumina, but it also decreases rapidly with temperature. Steatite has a thermal conductivity which is only 10 to 20% of that of alumina near room temperature but is not such a strong function of temperature. As long as the thermal properties can be considered to be constant over the temperature range of interest, the limiting cases of adiabatic heating for thick and infinitesimally thin films can be calculated from Eqs. (2-2) and (2-5), respectively. This enables one to estimate corrected temperatures in Figure 4-4 quite accurately.

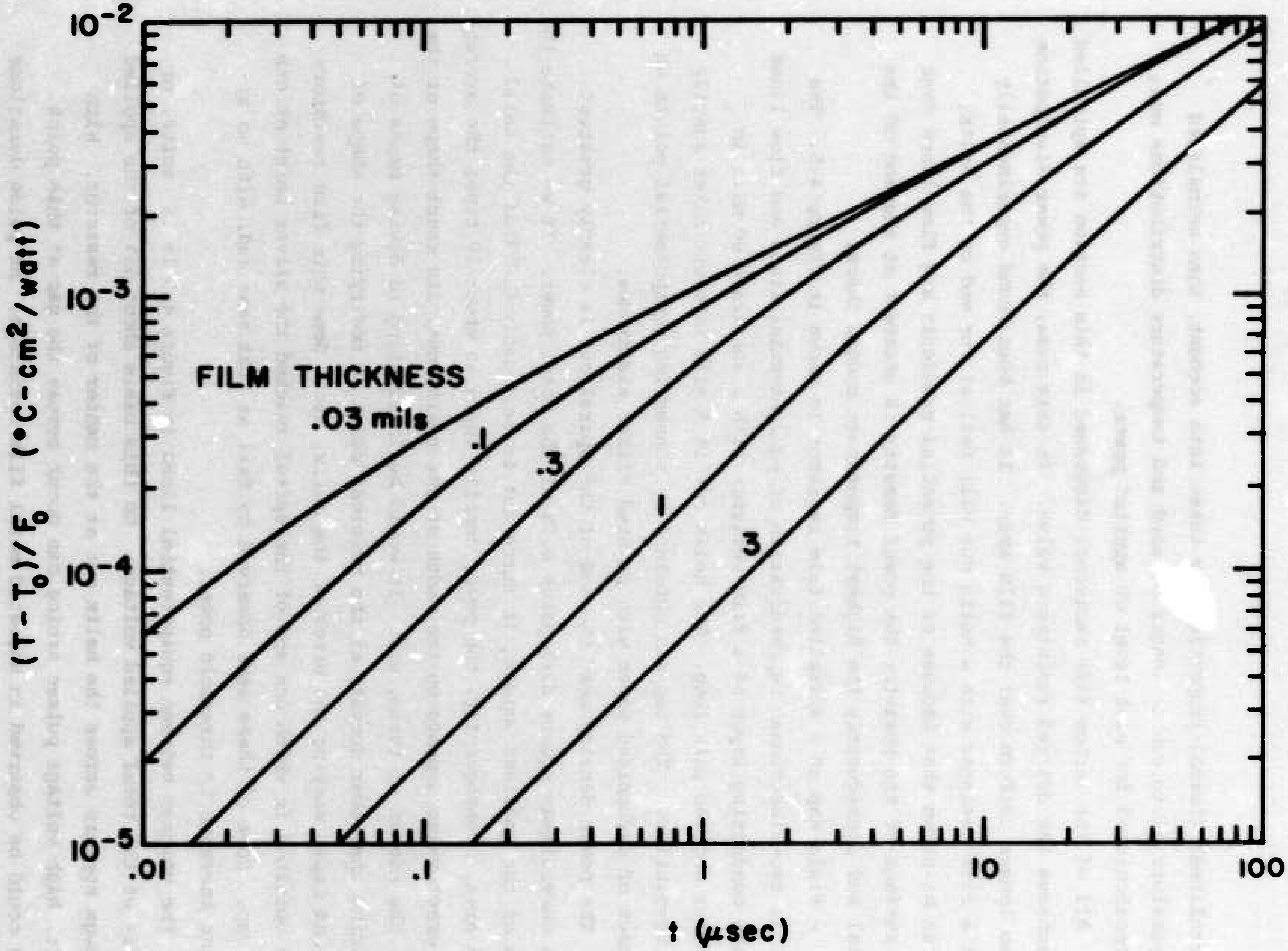


Figure 4-4. Peak temperature rise in carbon film resistors as a function of pulse duration.

If nonlinear thermal properties are taken into account, then normalized temperature plots can no longer be used and temperature distributions must be recalculated for each level of applied power.

All of the carbon film resistors discussed in this section are spiralled to achieve the desired resistance value. In this case, the power dissipation is no longer uniform over the film area. It has been found experimentally that a film resistor with a helix cut will fail at one end of the helix. It can be shown that because of the potential gradients and flow lines over the surface of the resistor the power density is greatest at the end of the spiral and consequently the highest temperature occurs there.

A field map of a spiralled film resistor is shown in Figure 4-5. The plot is two-dimensional representation of equipotential lines and flow lines in the conducting layer of a film resistor with a substrate 60 mils in diameter and 140 mils long. The helix cut is 5 mils wide and makes exactly two revolutions. The map was obtained by connecting equipotential points on a sheet of carbonized paper with painted silver electrodes.

The power density near the end of the spiral cut is clearly greatest. Each curvilinear square dissipates 0.2% of the total power. If we estimate the area of the smallest square, it turns out to be roughly 0.02% of the total film area. Consequently, the power density there is about 10 times the average. The exact value depends on the width of the spiral cut, its exact shape at the end, the number of turns, etc. It would be interesting to devise means of reducing the power density at the critical point by modifying the shape of the end caps, varying the pitch of the helix, etc. Some thin film resistors were obtained in which one end of the spiral reached the silver paint at one end cap. Some of these were observed to fail at that same end, with no apparent increase in threshold power.

The voltage between equipotential lines in Figure 4-5 is 15 volts, or 1 1/2% of the total applied voltage. On this basis about 65% of the applied voltage appears across the helix cut at the center of the resistor. With short, high voltage pulses arcing can occur across the gap at this point. This could be observed in uncoated metal film resistors. At pulse durations greater than 10 μsec, the failure was by a thermal mechanism. With pulses

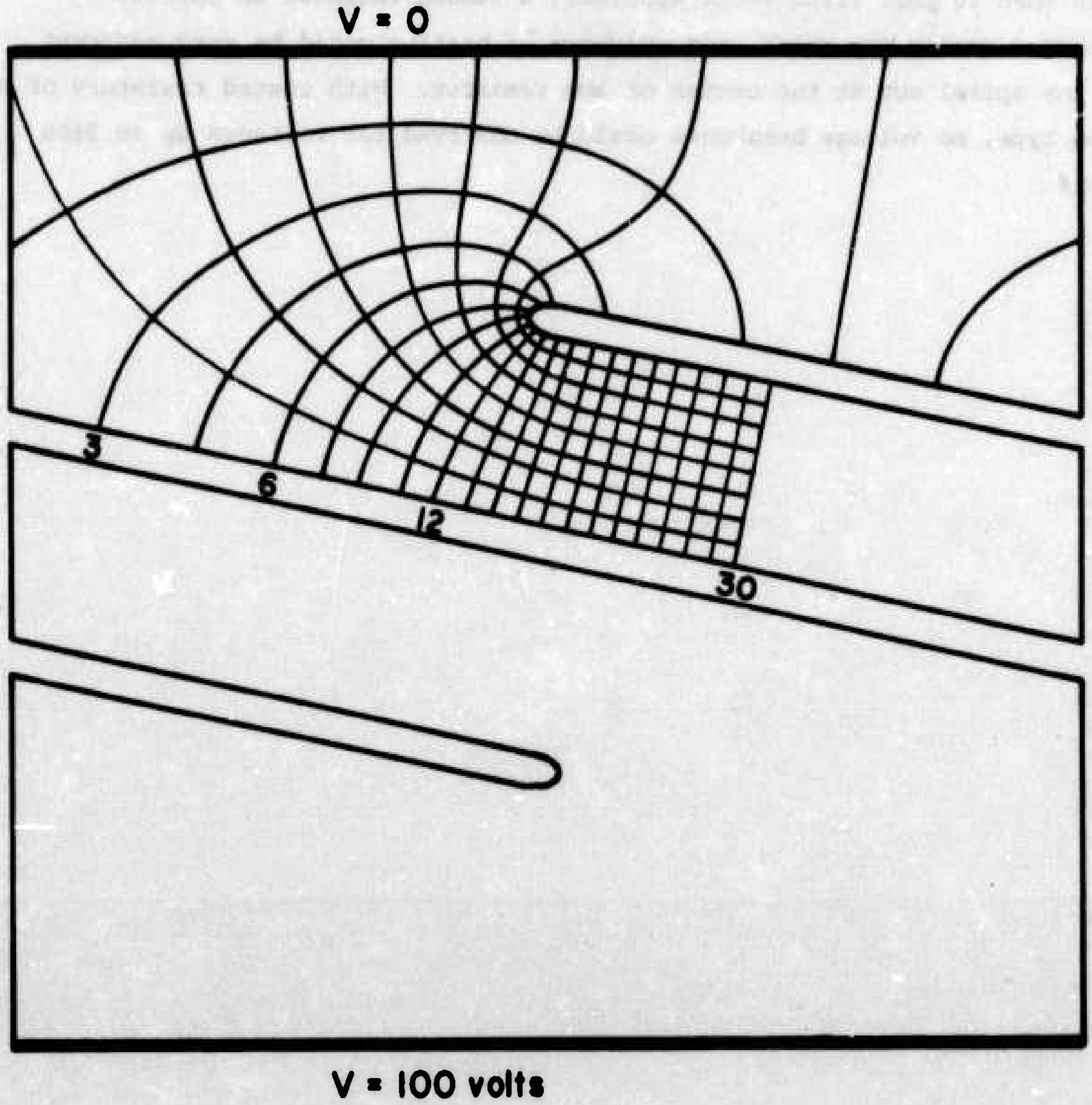


Figure 4-5. Equipotential lines and flow lines in the resistive layer of a spiralled film resistor.

less than 10 μsec (1500 volts applied), a sudden increase in current occurred during the pulse, and evidence of heating could be seen adjacent to the spiral cut at the center of the resistor. With coated resistors of the same type, no voltage breakdown could be observed for voltages up to 2400 volts.

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